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AD046 5437

FDL-TDR-64-54

A FULL BRIDGE TYPE STRAIN GAGE FOR USE AT ELEVATED TEMPERATURES

TECHNICAL DOCUMENTARY REPORT No. FDL-TDR-64-54

APRIL 1964

AIR FORCE FLIGHT DYNAMICS LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Project No. 1347, Task No. 134702

(Prepared under Contract No. AF 33(657)-11713 by
High Temperature Instruments Corporation, Philadelphia,
Pennsylvania; Benedict A. Sokolowski, Author)

NOTICES

200 - June 1965 - 448-43-958

FOREWORD

This report consists of development work carried out by High Temperature Instruments Corporation of Philadelphia, Pennsylvania, under Air Force Contracts No. 33(657)-9295 and No. 33(657)-11713. The contracts were initiated under Project No. 1347, "Structural Testing of Flight Vehicles," Task No. 134702, "Measurement of Structural Response." This project was initiated by the Air Force Flight Dynamics Laboratory Research and Technology Division. Technical coordination was provided by Mr. James Mullineaux, FDTE.

This report covers work conducted from June 1962 to November 1963.

ABSTRACT

The two-fold purpose directed under Contract No. AF 33(657)-9295 from June 1962 to March 1963 was as follows:

1. Development of a Full Bridge strain gage based on the concept of a Half Bridge type gage.

2. Gage installation methods usable to 2000° F.

The work conducted under Contract No. AF 33(657)-11713 from May 1963 to November 1963 consisted of a study of the strain and thermal characteristics of a Full Bridge strain gage over a temperature range of 600° to 2000° F. Thus the following tests were performed for the evaluation of a Full Bridge strain gage:

1. Measurement of bridge sensitivity factor at room and elevated temperatures.

2. Gage drift at constant temperature.

3. Response of gage to rapid radiant heating.

4. Leakage to ground resistance measurement.

5. Self heating effects.

It is shown that:

1. Gage installation by means of flame sprayed material was adequate for use to 2000° F.

2. Average bridge sensitivity factor was 7.0 ± 0.5 as measured at room temperature with a slight decrease at 1100° F.

3. Self heating effects of the gage were minimized.

4. Gage demonstrated a negligible drift rate to 1400° F.

5. Leakage resistance when measured at 2000° F., at a heating rate of 50° F./second was 10 megohms.

However, the gage material selected on the basis of previous tests was not fully acceptable for gage use to 2000° F., because a metallurgical transition occurs above 1500° F.

Publication of this technical documentary report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Holland B. Lowndes, Jr.
Actg. Chief, Structures Division
Air Force Flight Dynamics Laboratory

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SYMBOLS

K_s -Bridge sensitivity factor

G.F.-Gage factor setting

e -Strain, micro-inch per inch

σ, S -Stress, PSI

P -Load, lbs.

E_M -Modulus of elasticity, PSI

e_a -Axial strain, micro-inch per inch

e_T -Transverse strain, micro-inch per inch

F_T -Transverse sensitivity

α -Thermal coefficient of expansion

ΔT -Change in temperature, degrees F.

b -Thermal coefficient of resistivity

L_0 -Initial length, inches

L_1 -Final length, inches

ΔL -Change in length, inches

A -Cross sectional area, square inches

ΔE_g -Bridge output, millivolts

E_i -Bridge input, volts D.C.

a_L -Relative change of length

$\left.\begin{matrix} R_1 \\ R_2 \end{matrix}\right\}$ - Resistance, ohms

μ - Micro (10^{-6})

T/c - Thermocouple

I. INTRODUCTION

Previous work on strain gages by the High Temperature Instruments Corporation resulted in the development of a Half-Bridge gage whereby two adjacent arms, one unrestrained, experienced identical temperature variation. Due to its design this gage was drastically affected by self heating and had to be operated at low voltage with a resulting low output. It was envisioned that a full bridge configuration, a gage with two active arms, would increase the output with the same input voltage.

A Full Bridge strain gage (illustrated in Fig. 1) and installation techniques have been developed which permit the determination of static and dynamic strains above 1200° F.

The Full Bridge strain gage consists of the following components:

1. Two strain sensing wires forming opposite arms of a Wheatstone bridge.

2. Two temperature compensating arms, which are composed of slack wires of the same material as the sensing wires, and enclosed within fine silica tubes, are electrically connected between the two strain sensing arms to complete the Wheatstone bridge configuration.

3. Electrical lead wires which form each junction of the strain sensing arm and the compensating arm.

4. One thermocouple located close to the active and compensating arm.

5. A plastic carrier for easy handling and installation.

Manuscript released by authors July 1964 for publication as an RTD Technical Report

II. THEORETICAL CONSIDERATIONS

A. Construction and Theory of Operation

A Full Bridge resistance type strain gage consists of four elements that have identical thermal characteristics: two opposite strain sensitive arms which sense changes in strain and temperature while the remaining two arms sense only the changes in temperature.

The Full Bridge strain gage shown in Figure 1A uses two inactive temperature compensating arms and two active arms arranged in a Full Bridge configuration which can be treated as a single gage. The inactive arms are enclosed within miniature quartz tubes with sufficient slack in the wire to prevent strain from being transmitted from the test object to either of these two arms. The two remaining active arms are subjected to strain and temperature changes and are placed in the opposite arms of a Wheatstone bridge. Since all the wires forming the four arms of the Wheatstone bridge are secured in close proximity to each other and to the test object, both pair of arms are subjected to the same changes in temperature as the object, so that any unbalance in the bridge is indicative of the change in strain in the test object.

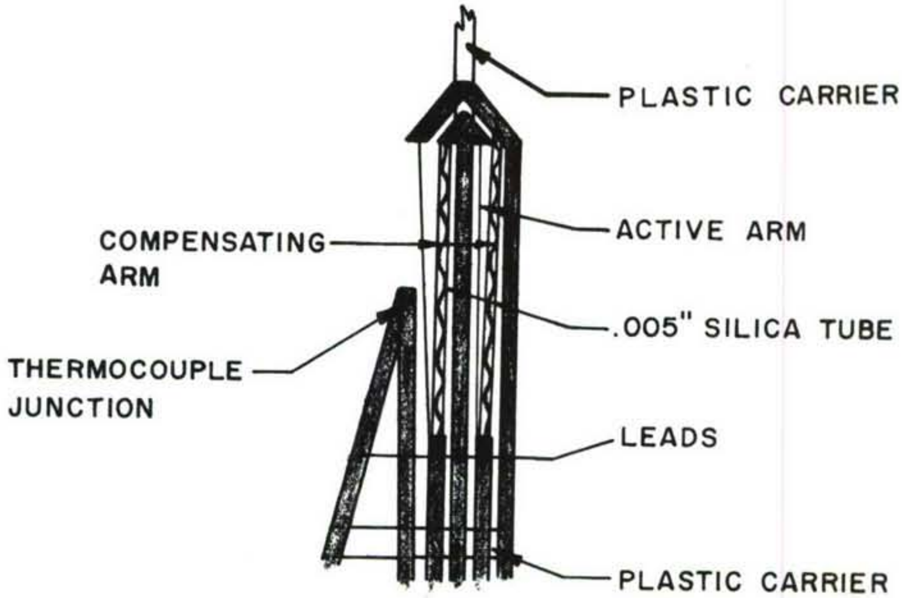
Its output is twice that of a Half Bridge or a single gage made of similar strain material.

B. Bridge Circuitry

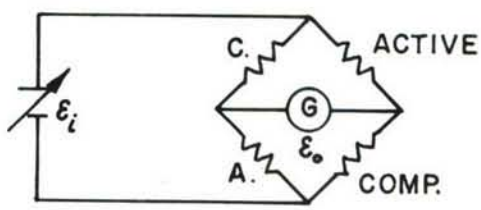
A basic Wheatstone bridge circuit is illustrated in Figure 1B. Since the active arms change simultaneously and in the same direction, they are located in the opposite arms of the bridge as indicated by R_2 and R_4.

Since the ratio of adjacent arms must be exactly equal before any strain is applied, the bridge must be balanced (reference Figure 1C) in order to obtain a zero bridge output. If an A.C. input voltage is applied, an additional balancing control is normally employed to compensate for the capacity difference of the bridge circuit.

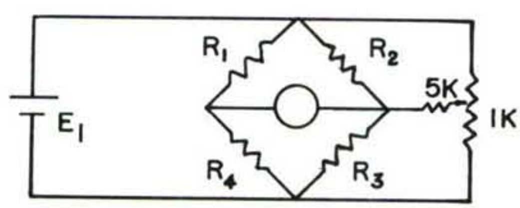
HT-1200, a platinum base alloy, was selected as material in the development of a Full Bridge strain gage because of its high gage factor, well defined repeatable resistance temperature relationship and because the alloy was expected to be corrosion resistant.



A- FULL-BRIDGE STRAIN-GAGE



B- WHEATSTONE-BRIDGE CIRCUIT



C- BALANCING CIRCUIT

FIGURE 1- FULL BRIDGE STRAIN GAGE AND CIRCUITRY

III. GAGE INSTALLATION METHODS

A. Substrate Material Stability

Oxidation of most metals occurs at high temperature when heated in air. The extent of this attack on the metals and alloys is determined by the physical properties of the formed scale.

Aluminum and chromium are the two alloying elements presently in use to form refractory oxides. With increased concentration of these alloys in content, the inner scale layer adjacent to the base metal becomes almost entirely a refractory oxide so that decrease in rate of oxidation can be expected.

The most important compound of heat resistant alloys is chromium. It forms a highly refractory oxide with nickel which is workable even when the percentage content of chromium is high. The improvement in the resistance of nickel to oxidation is concurrent with chromium additions up to its solubility limit. In quantities up to about 10% chromium, the oxide formed is nickel oxide (NiO) and with higher chromium contents the resulting oxide has the NiO crystal structure of chrome oxide (Cr_2O_3) which is more refractory than NiO and affords greater protection. The increased resistance to oxidation of NiCr alloys has been attributed to the presence of the Spinel ($NiO\text{-}Cr_2O_3$) compound which has been reported in alloys containing 15% to 20% chromium.

Aluminum improves resistance to oxidation. Low rates of oxidation are obtained only when a white aluminum oxide (Al_2O_3) scale forms over the surface of any aluminum alloy. Consequently, both oxides were used for gage installation for its use at elevated temperatures. Nickel Chrome oxide prevents oxidation of the base material while the aluminum oxide acts as a thermal barrier.

B. Surface Preparation

Surface preparation of specimens such as Inconel X, Rene 41, and Nimonic 90 were investigated prior to the application of flame sprayed coatings, and the methods selected were as follows:

1. The surface of each specimen was cleaned with acetone or other degreasing solution and then sand blasted. After degreasing, the specimen must be heated to 600° F. to char and drive oil from the pores of the metal. It is important that the oil, grease and other foreign matter be removed not only from the surface to be

coated but also from adjacent surfaces. Otherwise, the heat of the coating operation may cause grease or oil to run onto the area to be coated.

2. An alternate method consisted of etching the surface of the specimen with a solution which consisted of the following:

Water 1000 cc
Nitric acid 1000 cc
Hydrofluoric acid 150 cc

and then rinsing in a 1% neutralizing Ammonia Hydroxide solution.

Because of some warpage that was noted in the sand blasted specimens, the second method was selected in the surface preparation of all test specimens.

C. Flame Spray Techniques

An economic method of rapidly applying refractory oxides on a specimen was found in the use of the flame spray technique.

The flame spray method utilizes a special gun in depositing metal or ceramic (refractory oxide) particles on a specimen. The powdered metal or ceramic after being vaporized by the heat of the oxy-acetylene flame is ejected at high velocity from the gun nozzle and deposited on the target surface area.

The two-part coating evolved for high temperature strain gage installation was a nickel chrome alloy (NiCr) and aluminum oxide (Al_2O_3). The nickel chrome coating is applied first to retard oxidation of the base material and to give added bond strength to the refractory oxide coating.

A 5 mil coating of nickel chrome (Metco type 43C) is first applied on the specimen's prepared surface followed by a 3 mil soft porous coating of aluminum oxide (Metco type 105). No standard methods were devised for controlling the thickness of the sprayed material. The coating of alumina must be somewhat porous in order to resist the high thermal shock encountered and to improve effectiveness as a thermal barrier. This coating must be applied over an oxidation resistant base material such as NiCr. The NiCr coating is utilized in the "as sprayed" state.

The physical properties of thermo spray ceramic coating can be altered within rather wide limits by varying spray techniques.

The terms "soft" and "hard" represent the two extremes with any given type of ceramic coating. For soft coating, traverse speed, powder feed rate and distance from the nozzle to work are kept at a maximum for the particular material being applied and the work temperature is kept at a minimum. Soft coatings are more porous than are hard coatings and are therefore capable of more flexure and are much more resistant to thermal shock failure.

The bond to the base must be sufficiently strong to retain the coating in intimate contact with the base material. It must be able to withstand stresses caused by unequal expansion coefficients, otherwise the coating separates from the surface and a void exists at the interface. When this occurs, the base metal tends to oxidize as heat is applied and the coating will not adhere to the base.

D. High Temperature Cement

An investigation was made on various cements to determine their practical limits for strain gage installation. Among the cements tested were Armour's B-144 and B-52 and Allen's PBX cement.

The properties desired in a high temperature cement were as follows:

1. Ease of application.
2. Wet the surface readily.
3. Air dry quickly.
4. Cure with moderate heat.
5. Maintain good bond and electrical resistance on all materials to 1600° F., and usable to 2000° F. when applied on flame sprayed alumina coating.

Of the three cements tested, B-144 exhibited the necessary bonding characteristics and the best insulating properties.

Many of the commercially available cements provide an adequate bond but show an appreciable electrical leakage at high temperatures. The B-144 cement tends to overcome this deficiency by blending high purity oxides with selected bonding material.

To determine its corrosive action on the resistance of fine wire, a 10 mil nickel wire was imbedded into the cement. The cement was brush-coated on a prepared Inconel X specimen and cured at 600° F. for one hour. The specimen was then heated to

1500° F., and the resistance change of the wire measured at that constant temperature over a period of one hour. Since there was no change in electrical resistance of the wire, no corrosive effects were indicated.

E. Installation of Gages

The strain gage was held firmly in place on a prepared specimen by means of a cellulose tape placed across the top and bottom of the gage. Slight tension was applied during this process to maintain close proximity of the strain sensing wires to the specimen. High temperature cement (B-144) was then sparingly applied to the exposed gage by means of a brush, using a light stroke across the resistance wires.

To control the thickness of the cement, two parallel strips of cellophane tape, measuring 6 mils in thickness, were applied lengthwise adjacent to each side of the gage. The excess cement was smoothed off with a plastic strip which rode along on the cellophane tape. The tape was then removed and a uniform 0.006" thick coating remained.

After the cement had air dried for thirty minutes, the cellophane strips were removed and the remaining portions of the gage cemented.

The specimen was subjected to a one-half hour cure at 220° F., followed by a slow rise in temperature to 600° F., at the rate of 5° F./minute, and cured at that temperature for one hour, followed by a slow cooling cycle to room temperature at a similar rate.

F. Lead Wire Installation and Welding Techniques

Transition leads are required between the light gauge (0.005" diameter) strain gage wire and the instrumentation. The extension wires must withstand the same elevated temperatures as the specimen.

A high temperature connector, consisting of a group of insulated 10 mil platinum wires, was designed to provide extension leads for either laboratory or field instrumentation. This type of connector is illustrated in Figure 2. Four 10 mil platinum wires plus the Chromel-Alumel extension leads were separately enclosed in a magnesium oxide ceramic tubing and placed within 0.025" i.d. nickel tubing which was flattened and welded to a 5 mil Inconel X ribbon. The ribbon was then welded on the test specimen.

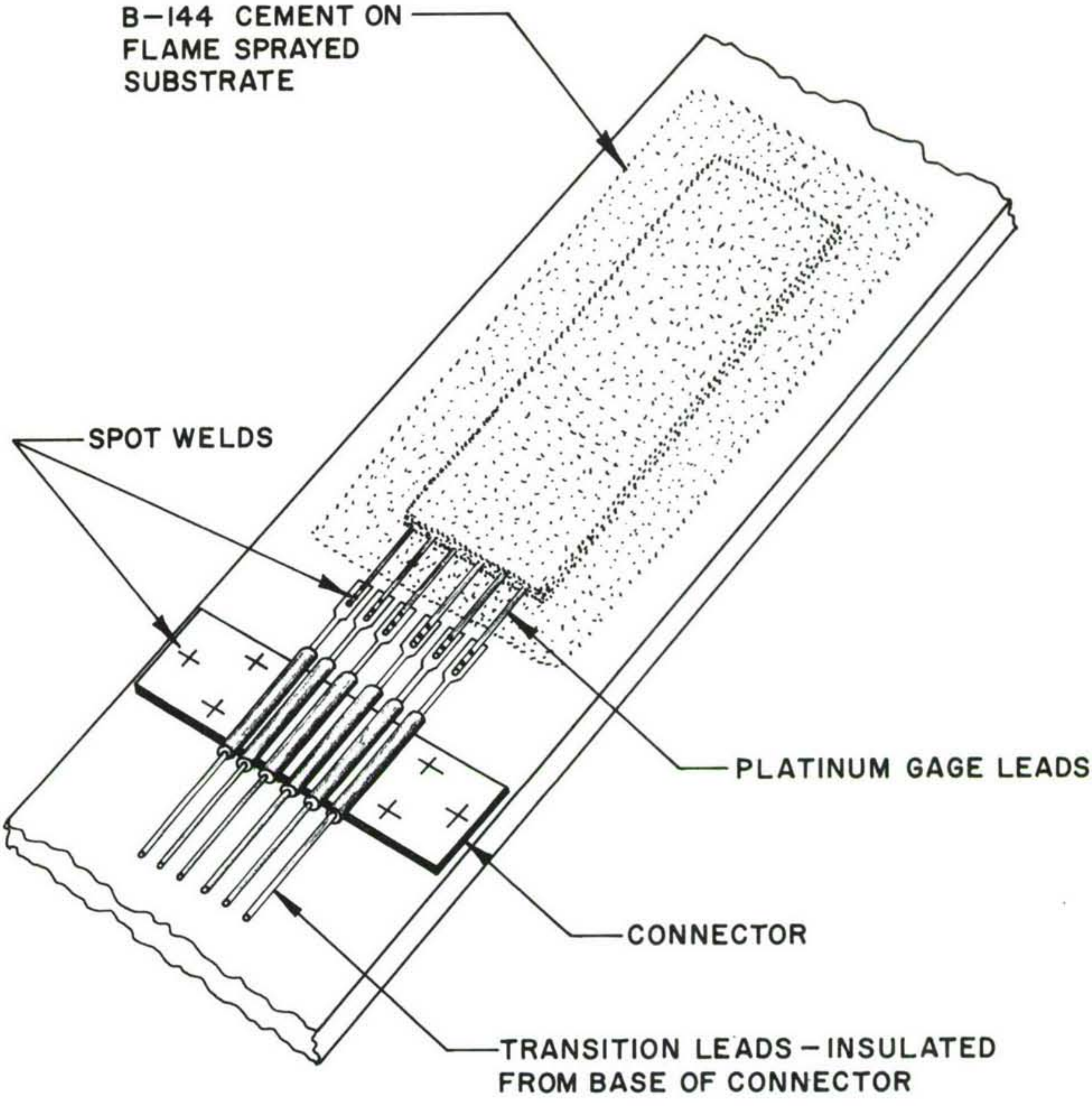


FIGURE 2 - TYPICAL GAGE AND CONNECTOR INSTALLATION

Proper welding techniques must also be utilized in the wiring connection of a Full Bridge strain gage. To obtain a good electric weld, the following conditions must be adhered to:

1. Power supply used in welding should be free from any line voltage fluctuations.

2. Proper electrodes with a flat surface should be perpendicular to the welding area.

3. Body motion should be minimized.

4. A correct watt-second charge and proper pressure should be applied to the material during the weld.

IV. TEST PERFORMANCE (Under Contract No. AF 33(657)-9295)

A. Test Procedure Methods at Steady State Condition

The following initial tests were performed on a Full Bridge strain gage when installed on coupon type test specimens, 0.050" x 1" x 6":

1. Gage resistance and leakage to ground measurements at room temperature.

2. Bridge sensitivity factor at room temperature.

3. Drift measurements.

4. Temperature sensitivity (apparent strain).

5. Zero shift.

6. Effects of temperature on leakage resistance.

7. Maximum gage current capacity at room and elevated temperatures.

8. Self heating effects.

9. Thermocouple effects.

An electrical and a zero balance check were initially conducted on each test specimen.

1. Gage resistance and the leakage to ground measurements were made at room temperature.

2. A bridge sensitivity check was performed on each gage at room temperature by applying a bending load from 0 to 400 grams, a maximum calculated strain of 364 micro inches per inch. The micro strain was measured on a strain indicator at a gage factor setting of 2.00 and the recorded strain measurement plotted against force.

3. Drift Measurements: The drift measurements were made in an oxidizing atmosphere. The instrumented specimen consisting of one thermocouple and a Full Bridge strain gage was placed inside a furnace. Electrical connections needed for the test unit's operation were completed. The bridge was initially balanced by

means of a balance box for zero strain while at room temperature. Readings were observed on a strain indicator at a gage factor setting of 2.000. The temperature of the furnace was increased in steps of 200° F. from 600° to 2000° F.

After stabilizing, the specimen was maintained at constant temperature for thirty minutes. The strain level and the temperature variation were then observed and recorded periodically throughout the entire test.

4. Temperature Sensitivity: The instrumented test specimen consisting of either a Half Bridge or a Full Bridge strain gage and a thermocouple was placed in a furnace. The bridge was balanced initially for zero strain.

Prior to the test an equivalent strain, as indicated by the bridge unbalance due to the shunting action of 50,000 ohms across the active arm, was noted on a strain indicator and the data recorded. The temperature in the furnace was increased to 2000° F. at a slow heating rate. The resultant strain, as indicated on the strain indicator at a gage factor setting of 2.00 was recorded and the corresponding change in temperature noted. Resultant data of temperature sensitivity vs. change in temperature was then plotted.

5. Zero Shift: As indicated by the unbalanced bridge signal, the zero shift was recorded at the completion of its cooling cycle. The bridge was rebalanced prior to its succeeding thermal cycle.

6. Effects of Temperature on Leakage Resistance: An instrumented test specimen with a Full Bridge and a thermocouple was placed inside an oven. The change in resistance between one of the strain wires and the specimen was monitored from 75° to 2000°F. The change in resistance was observed on a megohm meter and the data recorded. Resistance change was then plotted against a variation in temperature.

7. Maximum Gage Current Capacity: The maximum gage current capacity was determined by observing and recording the maximum input current applied to gage during its operation both at room temperature and 2000° F.

8. Self Heating Effects: The test specimen, while at room temperature, was initially balanced at a bridge input of 1 volt D.C. The output of the gage was recorded on the Y-axis with the temperature variation recorded on the X-axis of an X-Y recording instrument over a period of ten minutes while at constant input voltage and zero load. The bridge input voltage was then increased

from 1 to 8 volts D.C., in one volt increments, and its output monitored at each point while at zero load during a ten minute interval.

9. Thermocouple Effect: The test specimen was placed inside an oven. Electrical connections needed in the operation of the test unit were completed. The gage was initially balanced at a constant input voltage with its output connected to the Y-axis while the variation in temperature was recorded on the X-axis of an X-Y recording instrument.

The output of the gage was then monitored from 75° to 2000° F., with no voltage applied to the bridge.

Test Results

The evaluation tests completed on the Full Bridge strain gages were as follows:

1. Gage resistance and the leakage to ground measurements at room temperature: The gage resistance was a nominal 60 ohms for each arm. The leakage to ground averaged 100 megohms.

2. Bridge sensitivity factor: Bridge sensitivity factor (K_s) determined on six Full Bridge strain gages at room temperature is shown in Table I. The bridge sensitivity factor was determined by the following equation:

$$K_s = \frac{\text{Assumed gage factor setting x indicated strain}}{\text{Calculated strain}} \qquad (1)$$

A characteristic response of a typical Full Bridge strain gage for a strain vs. load relationship is illustrated in Figure 3.

The low K_s value for gage EH-2 is due to the faulty construction of the gage. A nominal bridge sensitivity factor desired was 6.5.

Consequently, no loss has been noted in the strain sensitivity factor due to addition of flame sprayed material. A typical strain sensitivity value of a single active arm of a Full Bridge strain gage (reference Table I, gage EH-9) has been determined as 3.31. This value agrees to an average strain sensitivity factor of an HT-1200 single element strain gage (reference Evaluation of Resistance Strain Gages at Elevated Temperatures, National Bureau of Standards, Progress Report No. 9).

TABLE I

FULL BRIDGE SENSITIVITY FACTOR VALUES AT 75° F.

Measurements recorded on a strain indicator at gage factor of 2.000.

K_s = Bridge sensitivity factor calculated for a 400 gram load (364 micro inch per inch)

Gage No.	Strain μ "/"	K_s
EI-1	1250	6.86
EH-2	915	5.04
EH-9	1205	6.62
EH-11	1300	7.14
EI-11	1140	6.27
EI-19	1200	6.60

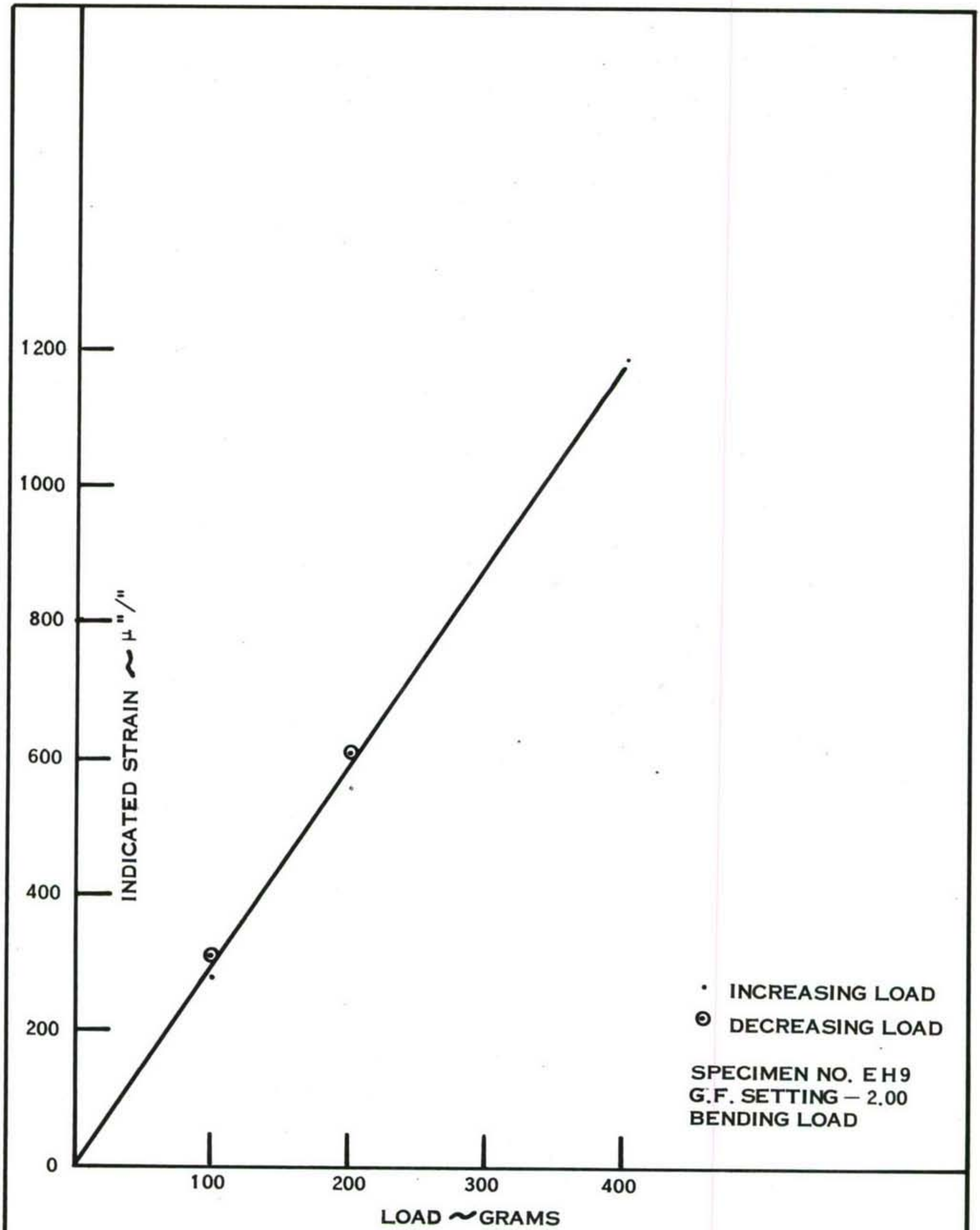


FIGURE 3 CHARACTERISTIC RESPONSE OF A TYPICAL FULL BRIDGE STRAIN GAGE

3. Drift: The drift behavior of two Full Bridge strain gages, EH-2 and EH-9 are shown in Table 2. Figure 4 shows drift behavior to 1400° F. of a Full Bridge strain gage installed on an Inconel X specimen.

Gage EH-2 installed on a Hastelloy B coupon specimen was subjected to two temperature cycles to 1600° F., followed by three additional cycles to 2000° F. Gage EH-9, also cemented to a Hastelloy B test specimen, was subjected to five repeatable temperature cycles to 2000° F.

Drift measurements were recorded on a strain indicator in micro-inches per inch at a gage factor setting of 2.00. A stop watch was used to measure the elapsed time at each constant temperature.

Gage drift occurs because of a change in the strain wire resistance at constant temperature with zero load. A reduction in cross sectional area by oxidation results in an increase in resistance or resistance can change at a constant elevated temperature either as a result of metallurgical change or by relief of residual stresses. However, the results cannot be distinguished between these various contributing factors.

A calibration performed on gage EH-2 at the completion of its fifth drift cycle resulted in a 10% decrease in strain sensitivity, see Figure 5. This was due to a decrease in bridge resistance from 63 to 49 ohms as a result of diffusion of the alloy.

TABLE 2

DRIFT CHARACTERISTICS OF TWO FULL BRIDGE STRAIN GAGES

Drift rate data on two Full Bridge strain gages installed on a Hastelloy B test specimen.

Drift rate at maximum test temperature, measured over a thirty minute period, micro-inches per inch per minute.

Measurements were recorded on a strain indicator at gage factor setting of 2.000.

Temperature Gage No.	1200° F. Drift Rate	1400° F.	1600° F.	1800° F.	2000° F.
1st Cycle					
EH-2	4.16	-33.40	-70.00	--	--
EH-9	7.00	--	- 7.06	--	-57.70
2nd Cycle					
EH-2	--	--	-10.70	--	--
EH-9	--	--	2.30	5.17	3.00
3rd Cycle					
EH-2	--	--	--	--	1.83
EH-9	--	--	--	7.0	2.00
4th Cycle					
EH-2	--	--	--	3.00	11.00
EH-9	--	--	--	2.83	6.66
5th Cycle					
EH-2	--	--	--	--	-17.03
EH-9	--	--	--	3.33	5.83

Tests were performed over the temperature range of 600° to 2000° F., however, the drift rate was negligible at temperatures below 1200° F.

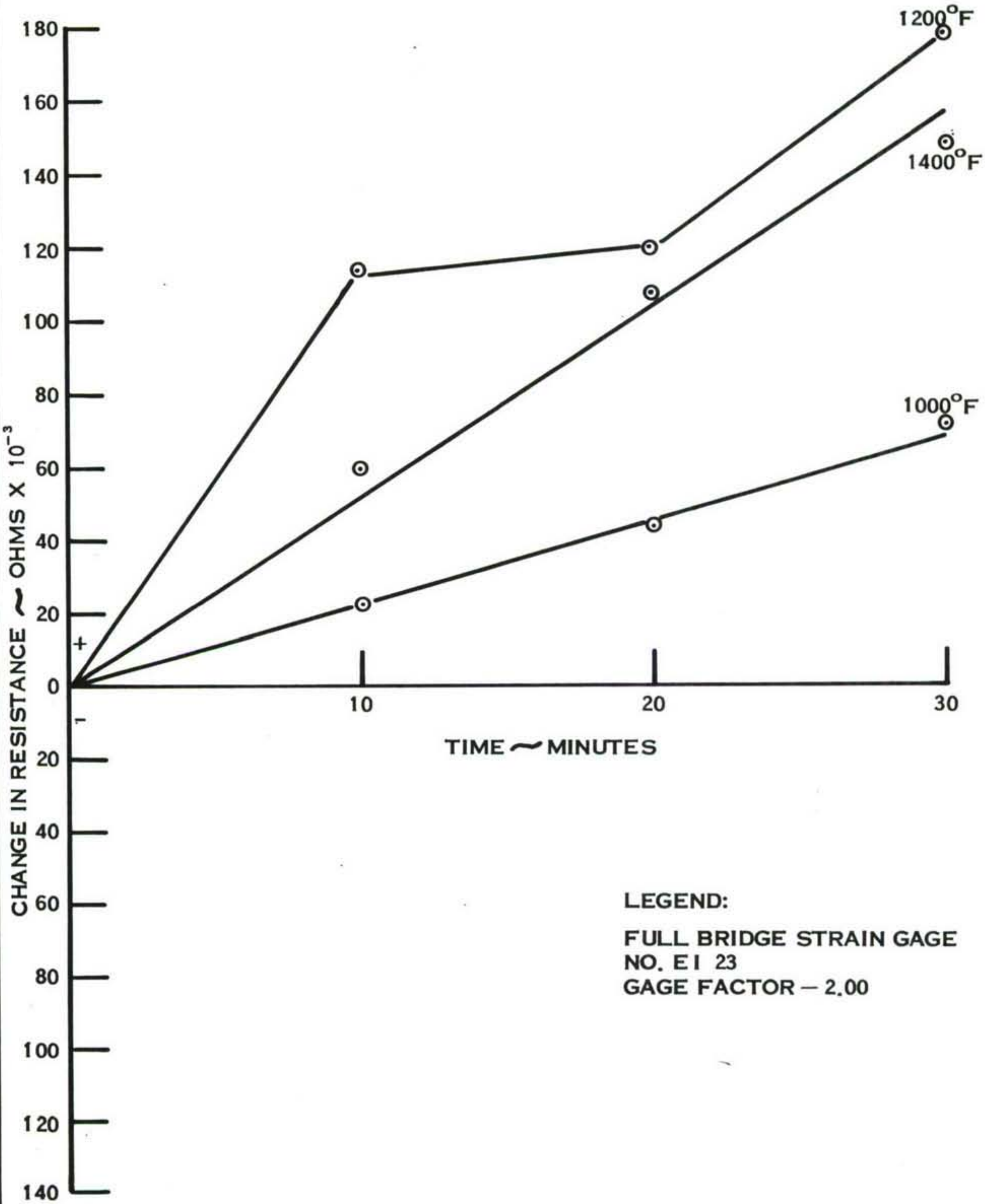


FIGURE 4 DRIFT CHARACTERISTICS OF A FULL BRIDGE STRAIN GAGE

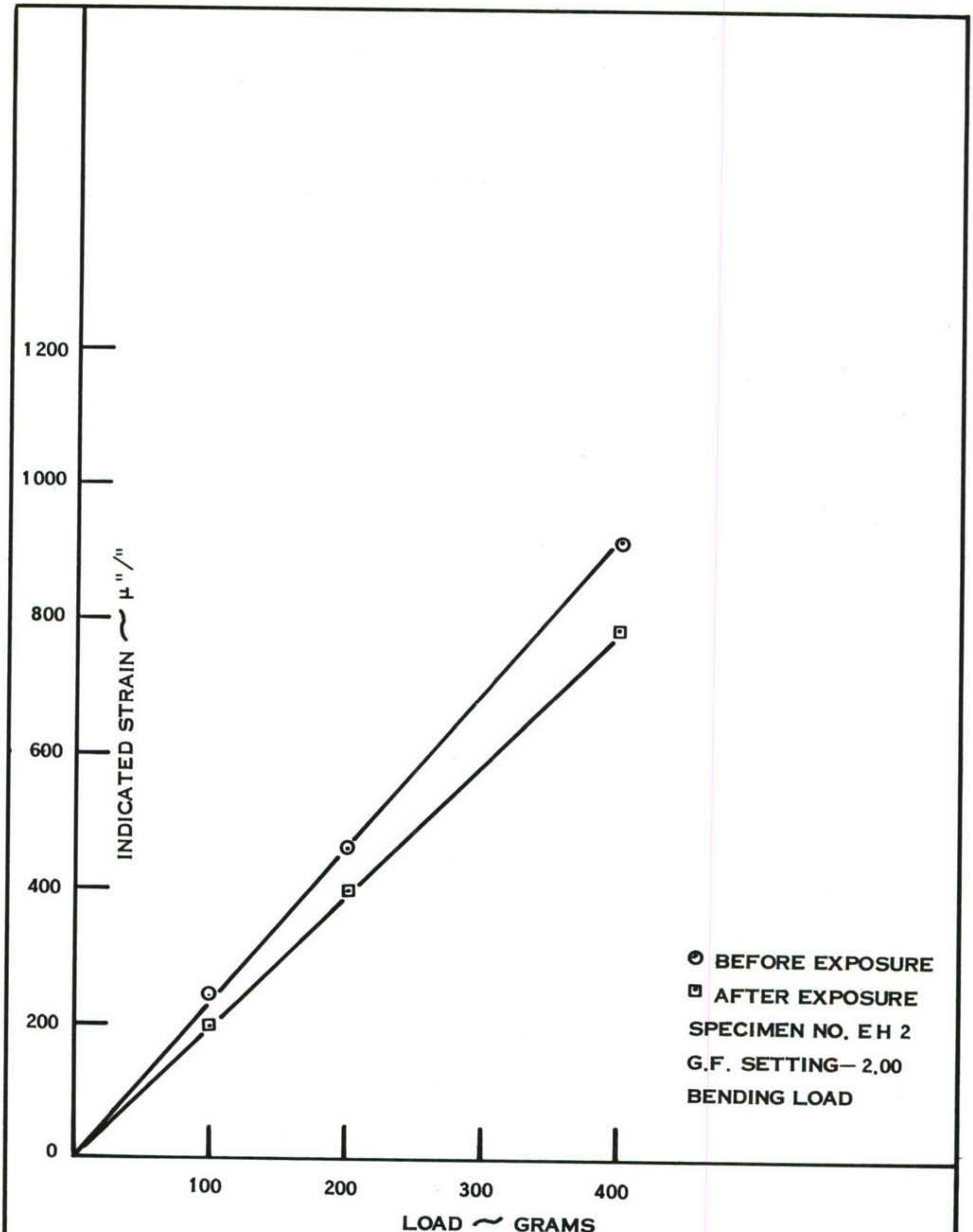


FIGURE 5 CHARACTERISTIC RESPONSE OF A FULL BRIDGE STRAIN GAGE AFTER EXPOSURE TO 2000°F

4. Temperature Sensitivity: Temperature sensitivity of gages EH-2 and EH-9 were recorded simultaneously during their drift test performances. At stabilization at each constant temperature the strain readings were noted and recorded for each gage prior to its thirty minute drift test. The recorded data is shown in Tables 3 and 4 and their corresponding curves for the first and fifth cycles in Figure 6.

The temperature sensitivity test performed on a Full Bridge strain gage when installed on an Inconel X specimen is shown in Table 5 and the resultant plot in Figure 7.

Results of the above tests indicated a linear rise to 1500°F., however, a sudden change was noted at 1600° F. Additional cycles, nevertheless, showed gage resistance stability and a decrease in temperature sensitivity.

This transition occurring at 1600° F., is due to some loss of Iridium in the Platinum base alloy, because of formation and volatilization of the oxide.

TABLE 3

EFFECTS OF TEMPERATURE SENSITIVITY ON A FULL BRIDGE STRAIN GAGE (EH-2)

GAGE No. EH-2

Specimen material: Hastelloy B.

Strain recorded in micro-inches per inch at a gage factor = 2.00.

Temp. ° F.	1st Cycle Strain Micro "/"	2nd Cycle Strain Micro "/"	3rd Cycle Strain Micro "/"	4th Cycle Strain Micro "/"	5th Cycle Strain Micro "/"
75	--	--	--	--	--
600	4135	2090	2785	5460	2715
800	5670	2280	3095	6355	3120
1000	6995	2220	3130	6850	3335
1200	7810	2070	3040	7115	3345
1400	9715	2200	3060	7390	2265
1600	15375	1370	2805	7060	2655
1800	--	--	1410	7580	2085
2000	--	--	1735	6830	1045

Drift and Temperature Sensitivity performed simultaneously.

TABLE 4

EFFECTS OF TEMPERATURE SENSITIVITY ON A FULL BRIDGE STRAIN GAGE (EH-9)

GAGE No. EH-9

Specimen material: Hastelloy B

Strain recorded in micro-inches per inch at a gage factor of 2.00.

Temp. ° F.	1st Cycle Strain	2nd Cycle Strain	3rd Cycle Strain	4th Cycle Strain	5th Cycle Strain
75	--	--	--	--	--
600	4550	3745	3905	3290	2710
800	5375	4560	4670	3910	3150
1000	6860	4940	5065	4260	3385
1200	8780	5415	5430	4460	3420
1400	10300	5470	5585	4610	3385
1600	11500	5620	5625	4510	3295
1800	9700	5780	5570	4435	3050
2000	9000	5990	5960	4135	2740

Drift and Temperature Sensitivity performed simultaneously.

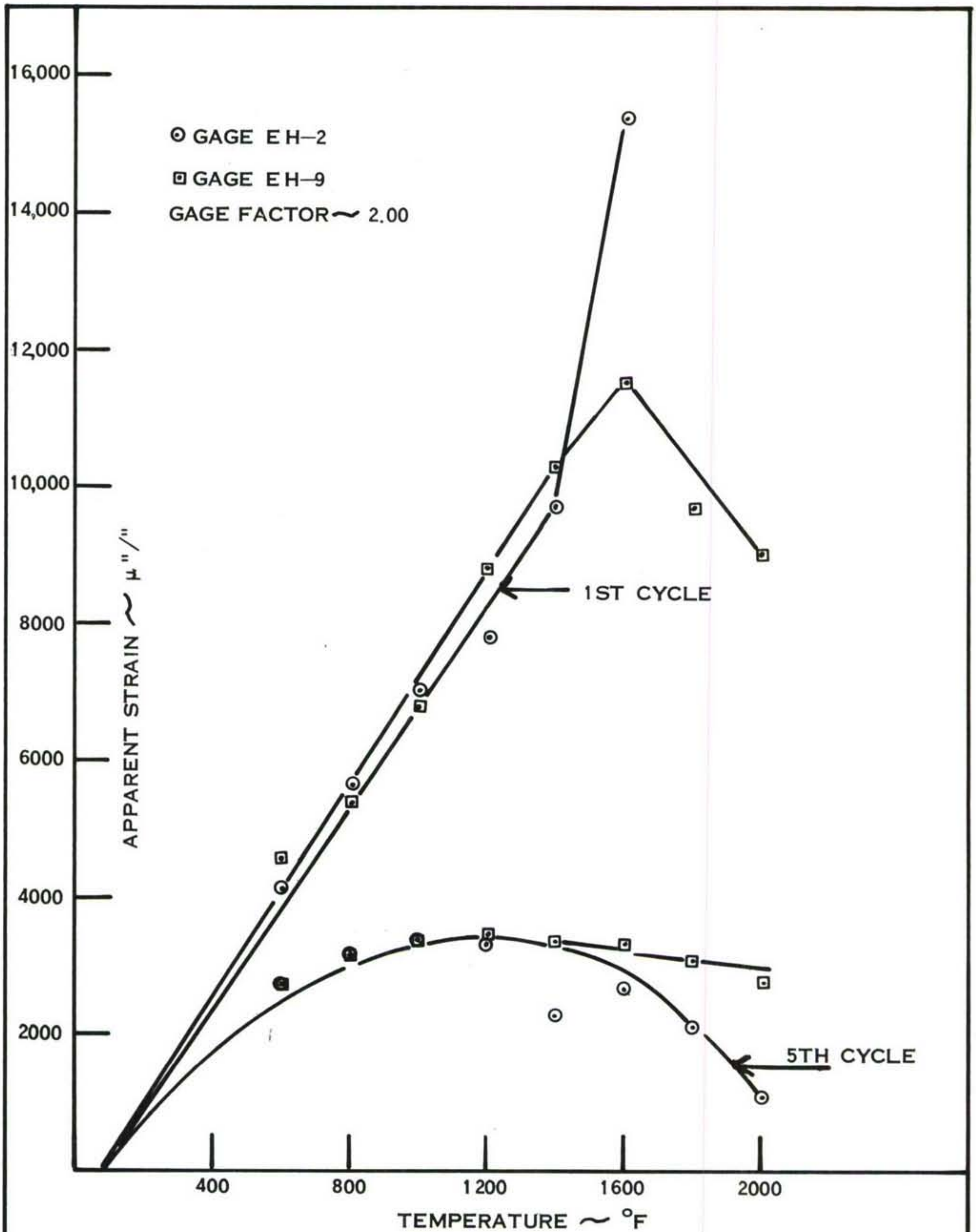


FIGURE 6 APPARENT STRAIN OF TWO FULL BRIDGE STRAIN GAGES ON HASTELLOY B

TABLE 5

EFFECTS OF TEMPERATURE SENSITIVITY ON A FULL BRIDGE STRAIN GAGE (EI-1)

GAGE NO. EI-1

Specimen material: Inconel X

Strain recorded in micro-inch per inch at a gage factor of 2.00.

Duration of test: 2-1/2 hours.

Temp. ° F.	Temperature Sensitivity Micro Inches per Inch	Elapsed Time Minutes
75	0	0
600	3290	30
1000	5490	62
1400	13725	95
1500	14500	109
1600	15370	117
1800	14200	135
2000	13000	150

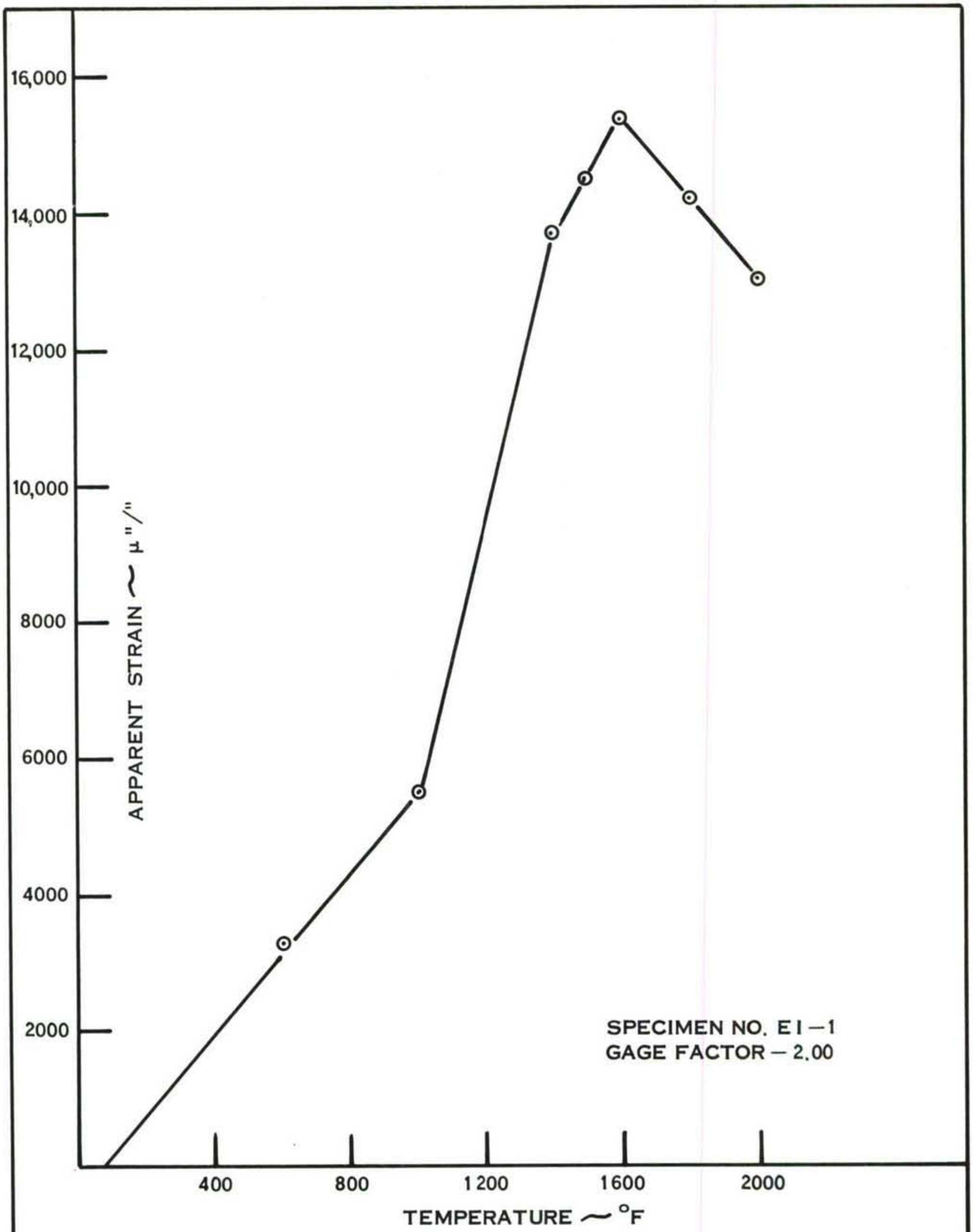


FIGURE 7 APPARENT STRAIN OF A FULL BRIDGE STRAIN GAGE ON INCONEL X

5. Zero Shift: Zero shift during its first thermal cycle to 2000° F. was approximately 3000 micro inches per inch for a Full Bridge strain gage as indicated on an SR-4 strain indicator at a gage factor setting of 2.00.

6. Leakage resistance to ground measurements between the Full Bridge strain gage and the test specimen at a steady state condition is shown in Table 6.

7. Maximum gage current capacity at room and 2000° F., was measured at 300 milliamps.

8. Self heating effects demonstrated on a Full Bridge strain gage were negligible at 5 volts D.C.; however, at 8 volts D.C., the time required for gage stabilization was twenty minutes.

9. No significant thermocouple effects were detected on Full Bridge strain gages with Platinum extension leads when subjected to a temperature range from 75° to 2000° F.

TABLE 6

EFFECTS OF TEMPERATURE ON LEAKAGE TO GROUND RESISTANCE ON A FULL BRIDGE STRAIN GAGE

GAGE NO. EI-3

Specimen Material: Inconel X

Resistance measurements made on a Weston Meg Ohm Meter

Gage installation was made three months prior to the test.

Temp. ° F.	Resistance Megohms	Time Elapsed Minutes	Remarks
75	9000	0	1st heating cycle to 1600° F.
600	200	11	
1000	10	23	
1200	3	33	
1400	1.5	42	
1500	1	52	
1600	.1	60	
1000	10	--	1st cooling cycle to 1000° F.
1000	10	0	2nd heating cycle to 1740° F.
1500	1	10	
1740	.1	20	

Transient Heating Conditions

A transient heating test facility was used in the performance of the following tests:

1. Effects of heating rates on temperature sensitivity and leakage resistance.

2. Gage to gage and cycle to cycle repeatability.

3. Zero shift.

4. Effects of thermal shock on gage installation.

5. Effects of bridge voltage on temperature sensitivity.

The test facility consists of the following units:

Recorder Controller (Research, Inc.) Model No. 4080
Power Regulator (Research, Inc.) Model No. 4079
Thermocouple Reference Junction (Thermo Electric)
150° F. Auto Ref.
Quartz 1200 watt Infrared Lamps (G.E. T-3)
Gold plated reflector units (Research, Inc.)

The Recorder Controller unit is contained in a caster mounted rack. The rack accommodates five modules containing two controllers each. The module is completely self-contained and operates from a 115 volt AC power source.

The main function of the Recorder Controller is to control the radiant energy of the quartz lamp heaters by proportioning the AC power in response to an error signal. The controller unit electrically sums the output of a thermocouple, installed on a test specimen, with a reference emf proportional to a desired temperature. The difference emf (error voltage) is then amplified sufficiently to control the output of the associated AC power regulator and thus control the power delivered to the quartz heaters.

The Thyratron Power Regulator regulates the power delivered to each radiant unit. Each module is rated at 40 amperes at 220 volts.

The thermocouple reference junction, Thermo Electric Auto Ref., is designed to maintain a constant 150° F. temperature. It is used in conjunction with the Recorder Controller unit.

G. Test Procedure

1. Temperature Sensitivity: A test specimen, 0.050" x 6" x 1" instrumented with two Chromel/Alumel thermocouples and either a Half Bridge or a Full Bridge strain gage, was placed between two separately powered gold reflector units. Each unit enclosed six 1200 watt quartz heaters. A one inch separation existed between the two reflectors. Electrical connections were completed between the two thermocouples and the Reference Junction unit for transient heat control.

The Half Bridge strain gage and two dummy resistors were connected to form a Wheatstone bridge. The bridge of either gage was balanced initially for zero millivolt reading and its output applied to the Y-axis of an X-Y recording instrument.

A millivolt deflection, corresponding to an equivalent strain, was recorded on the Y-axis by shunting 50,000 ohms across each of the two active arms. This millivolt output was proportional to the equivalent strain recorded on the strain indicator.

The specimen was subjected to a transient heating rate of approximately 50° F./second. The temperature sensitivity (apparent strain) of the gage was recorded on the Y-axis while the variation in temperature was recorded on the X-axis of the X-Y Recorder.

The temperature sensitivity as recorded over the temperature range 80°-2000°-80° F., constitutes one thermal cycle. A zero shift of the gage was indicated by the unbalanced millivolt output recorded at room temperature at the end of its cooling cycle. The zero shift was first recorded and the bridge rebalanced by shunting across the inactive arm prior to each succeeding thermal cycle.

The leakage resistance to ground measurements for various heating rates were performed in accordance with the circuitry shown in Figure 8. Electrical connections between one of the strain gage wires and the specimen were completed by means of a test box. The change in leakage resistance was recorded on the Y-axis while the temperature change of the specimen was measured on the X-axis of an X-Y Recorder. An external power supply delivered the voltage to the test box unit. A calibration of known leakage resistance to ground was simulated by shunting values of 10, 5 and 1 megohm resistance across one leg of the Wheatstone bridge and recording its millivolt output. The test was conducted over a temperature range from 80°-2000°-80° F., and the result plotted directly on the X-Y Recorder.

2. Repeatability of the gage was determined by subjecting the Full Bridge strain gage to five or more consecutive thermal cycles (75-2000-75° F.) and recording its response (apparent strain vs. temperature) by means of an X-Y Recorder.

3. Zero shift was determined by the unbalanced bridge signal at the completion of its cooling cycle.

4. Effects of thermal shock on gage installation were determined by subjecting the instrumented specimen to 2000° F., for five seconds, followed by quick cooling in ice water. A visual observation was made of the gage installation after each thermal shock test.

5. Effects of bridge voltage on temperature sensitivity of a Full Bridge strain gage was determined by subjecting the strain gage to temperature change with variation in bridge voltage. The bridge was balanced initially for zero output at each specified voltage. The resultant apparent strain was then recorded over the temperature range 80°-1200°-80° F., on an X-Y Recorder.

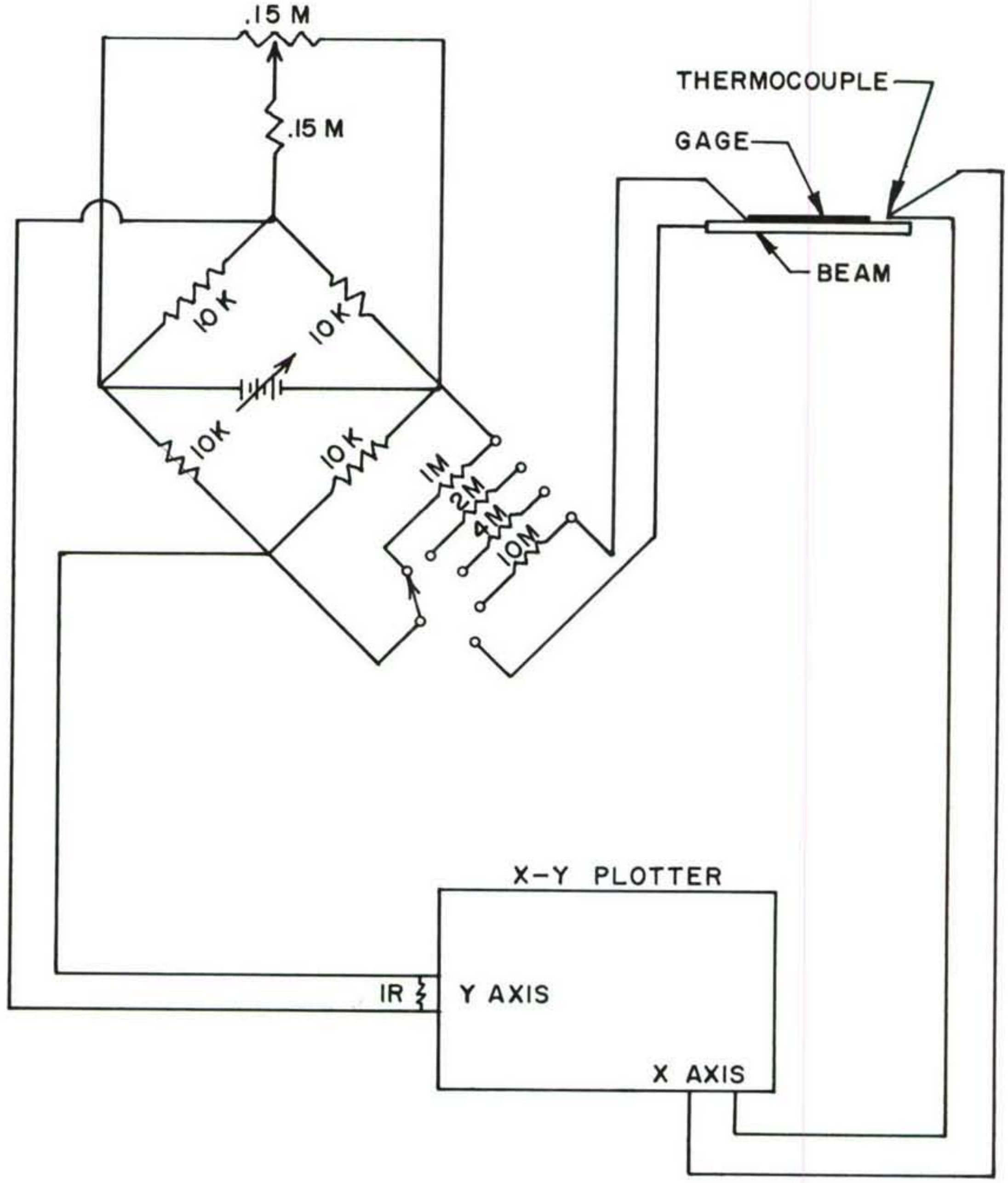


FIGURE 8– TEST UNIT FOR MEASUREMENT OF LEAKAGE RESISTANCE DURING TRANSIENT HEATING

H. Transient Heating Test Results

Results of tests performed at a heating rate of 50° F./second, on either a Half Bridge or a Full Bridge strain gage are indicated below.

1. Leakage resistance test performed on a Half Bridge gage is shown in Table 7. Effects of heating rate on temperature sensitivity are indicated in Tables 8 and 9 for a Half Bridge strain gage and in Table 10 for a Full Bridge strain gage.

2. The gage to gage and cycle to cycle repeatability on an HT-1200 gage are shown in Figures 9 through 11.

3. Zero shift during its first thermal cycle to 2000° F., is approximately 1500 micro-inches per inch for a Half Bridge strain gage and approximately 3000 micro-inches per inch for a Full Bridge strain gage as indicated on a strain indicator at a gage factor setting of 2.00.

4. The strain gage installation after being subjected to ten cycles of thermal shock still remained intact. There was no spalling or cracking of the cement or the substrate material after completion of the test.

5. Effects of bridge voltage on temperature sensitivity of a Full Bridge strain gage, as shown in Table 11, does not indicate a linear change. The maximum temperature reached was 1200° F.

TABLE 7

EFFECTS OF TRANSIENT HEATING ON LEAKAGE TO GROUND RESISTANCE ON A FULL BRIDGE STRAIN GAGE

Leakage to Ground resistance measurement

Date of Test: 10/20/62 and 11/6/62

Heating Rate: 50° F./second

Specimen Material: Inconel X.

Temp. ° F.	Resistance Megohms	Remarks	
1st Cycle			
75	100	Nickel chrome coating	none
1200	7	Aluminum oxide coating	0.002" thick
1500	1.5	Total thickness	0.002"
1900	.8		
2000	.3		
2nd Cycle			
75	100	Nickel chrome coating	0.012"
1300	100	Aluminum oxide coating	0.003"
1900	7.5	Total thickness	0.015"
2000	7.		

Increasing thickness of aluminum oxide by 0.004" to 0.007" for a total thickness of 0.019" increased the leakage to ground resistance measurement from 7 to 10 megohms at 2000° F.

A visual observation was made of the resistance on a multimeter and the data recorded manually.

TABLE 8

EFFECTS OF TRANSIENT HEATING ON TEMPERATURE SENSITIVITY OF A HALF BRIDGE STRAIN GAGE

GAGE NO. 2

Heating Rate: 50° F./second (1-8 cycles)

Specimen Material: Inconel X

Bridge Voltage: 2 volts D.C.

Strain measurement based on gage factor setting of 2.000.

Cycle	Max. Temp. ° F.	Apparent Strain at Max. Temp. Micro "/"	Zero Shift Micro "/"	Remarks
1	600	1880	none	
2	1200	4000	none	
3	2000	3000	600	Zero shift on 1st cycle to
4	2000	3000	none	2000° F.
5	2000	3000	none	
6	2000	3000	none	
7	2000	3000	none	
8	2000	3000	none	
9	2000	2700	none	Heating rate dec.to 25°F/sec.
10	2000	2700	none	Heating rate inc.to 100°F "
11	2000	2700	none	for cycles 10-12.
12	2000	2700	none	
13	--	--	--	Gage failed during the heating cycle however the bonding remained intact.

Bridge was balanced and re-zeroed before each succeeding thermal cycle.

TABLE 9

EFFECTS OF TRANSIENT HEATING ON TEMPERATURE SENSITIVITY OF A HALF BRIDGE STRAIN GAGE

GAGE NO. 4

Date of Test: 10/20/62

Heating Rate: 50° F./second

Specimen Material: Inconel X

Bridge Voltage 2.0 volts D.C.

Strain measurement based on gage factor setting of 2.000.

Cycle	Maximum Temp. ° F.	Apparent Strain at Max. Temp. Micro "/"	Zero Shift Micro "/"	Remarks
1	600	1950	none	
2	1200	4200	none	
3	2000	4050	1500	Zero shift on first cycle to 2000° F.
4	2000	2400	none	
5	2000	2400	none	
6	2000	2400	none	
7	2000	2400	none	
8	2000	2400	none	
9	2000	2400	none	
10	2000	2400	300	
11	2000	2400	none	
12	2000	2400	none	
13	00	00	--	Gage failed at the weld during heating cycle, bond remained intact.

Bridge was balanced and re-zeroed before each succeeding thermal cycle.

Rcal equivalent at 50K was approximately 640 micro inches per inch.

TABLE 10

EFFECTS OF TRANSIENT HEATING ON TEMPERATURE SENSITIVITY OF A FULL BRIDGE STRAIN GAGE

GAGE NO. EH-11

Date of Test: 11/5/62

Specimen Material: Hastelloy-B

Flame Sprayed Material - NiCr 0.006" thick
Al_2O_3 0.003" "
Gage thickness 0.010" (Gage plus B-144 cement)
Total thickness 0.019".

Bridge voltage - 2.0 volts D.C.

Strain measurements based on gage factor setting of 2.000.

Cycle	Maximum Temp. ° F.	Apparent Strain at Max. Temp. Micro "/"	Heating Rate ° F./sec.	Zero Shift Micro "/"
1	1200	2550	50	150
2	2000	7200	50	none
3	2000	7200	50	none
4	2000	7200	50	none
5	2000	7200	100	300
6	2000	7200	100	none
7	2000	7200	100	none
8	2000	7200	25	none

Rcal equivalent @ 50K = 560 micro-inch per inch at gage factor setting of 2.000.

Gage resistance = 60 ohms.

Bridge was re-balanced and re-zeroed before each succeeding thermal cycle.

TABLE 11

EFFECTS OF BRIDGE VOLTAGE ON TEMPERATURE SENSITIVITY OF A FULL BRIDGE STRAIN GAGE DURING TRANSIENT HEATING

GAGE NO. EI-19

Date of Test: 2/16/63

Heating Rate: 50° F./second

Specimen Material: Inconel X.

Strain Measurement based on gage factor setting of 2.000.

Cycle	Maximum Temp. ° F.	Apparent Strain at Max. Temp. Micro "/"	Bridge Voltage DC	Remarks
1	1200	3720	1 volt	Rcal equivalent at
2	1200	3720	1 "	50K = 560 micro inches
3	1200	7440	2 "	per inch
4	1200	7440	2 "	
5	1200	8900	3 "	
6	1200	8900	3 "	
7	1200	11160	4 "	
8	1200	11160	4 "	
9	1200	11160	4 "	
10	1200	15020	5 "	
11	1200	15020	5 "	
12	1200	18975	6 "	
13	1200	18975	6 "	

Bridge was re-balanced and re-zeroed prior to the start of each succeeding cycle.

Rcal equivalent was determined by shunting 50,000 ohms across each of the two active arms and recording their average strain.

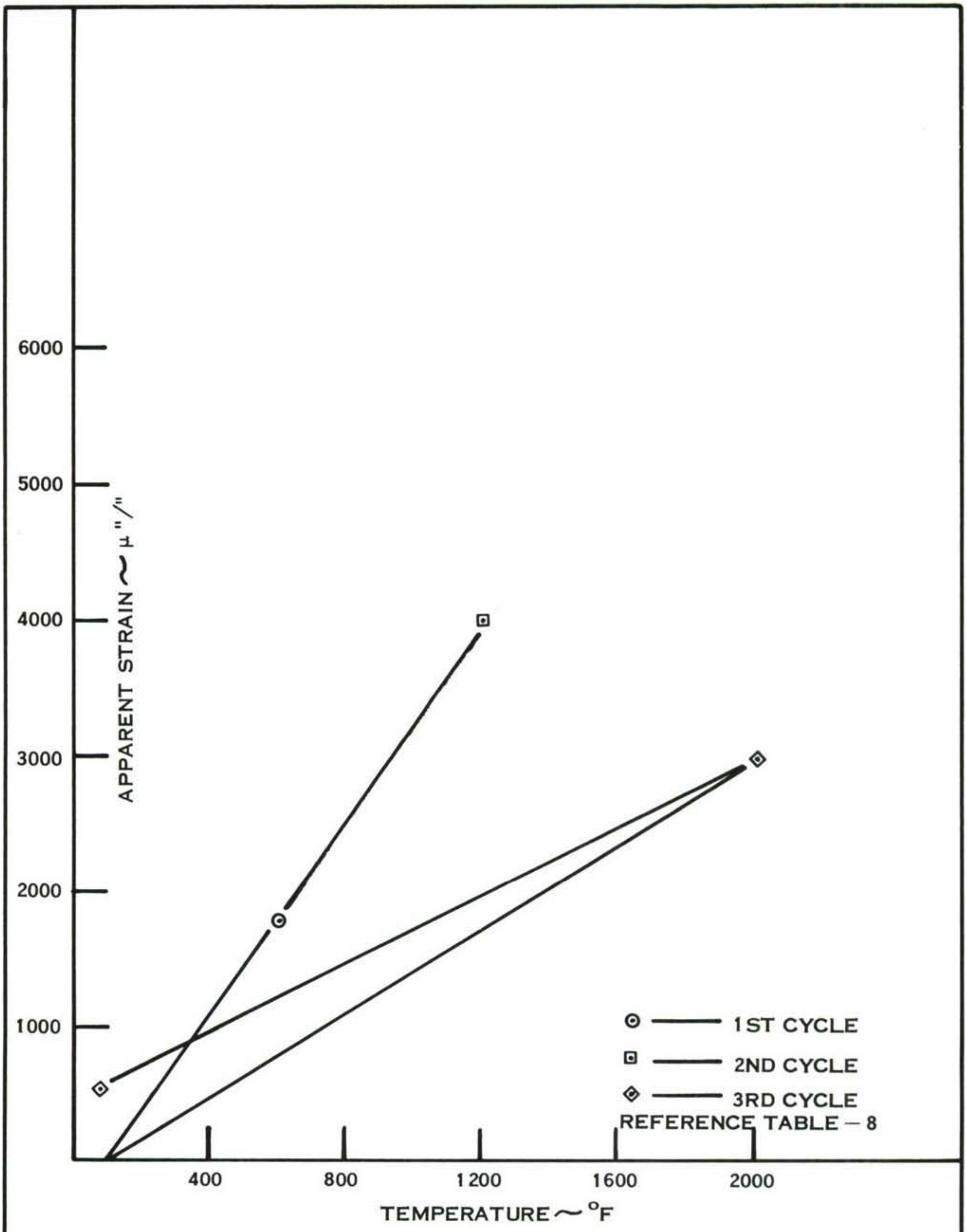


FIGURE 9 APPARENT STRAIN OF A HALF BRIDGE STRAIN GAGE ON INCONEL X DURING TRANSIENT HEATING

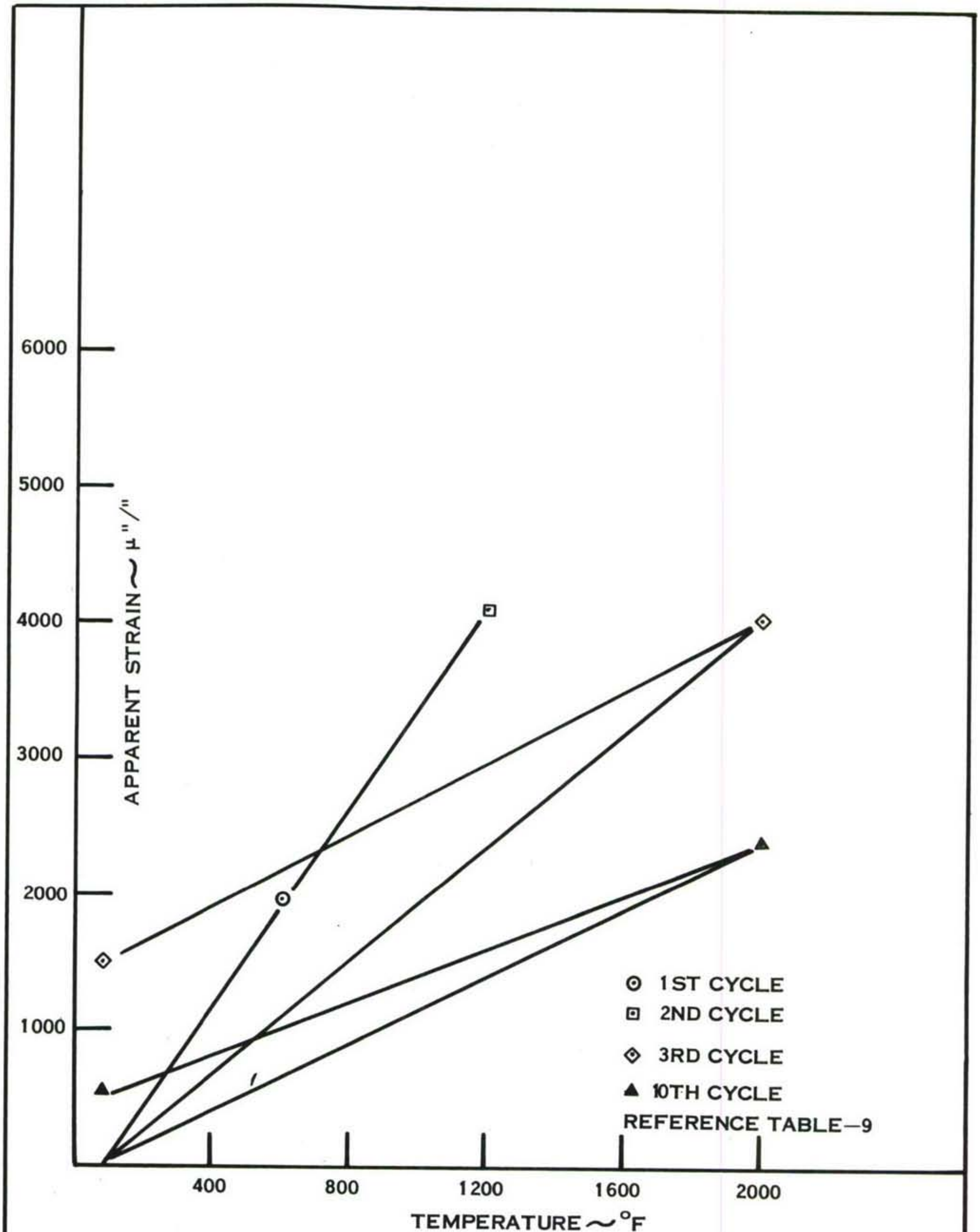


FIGURE 10 APPARENT STRAIN OF A HALF BRIDGE STRAIN GAGE ON INCONEL X DURING TRANSIENT HEATING

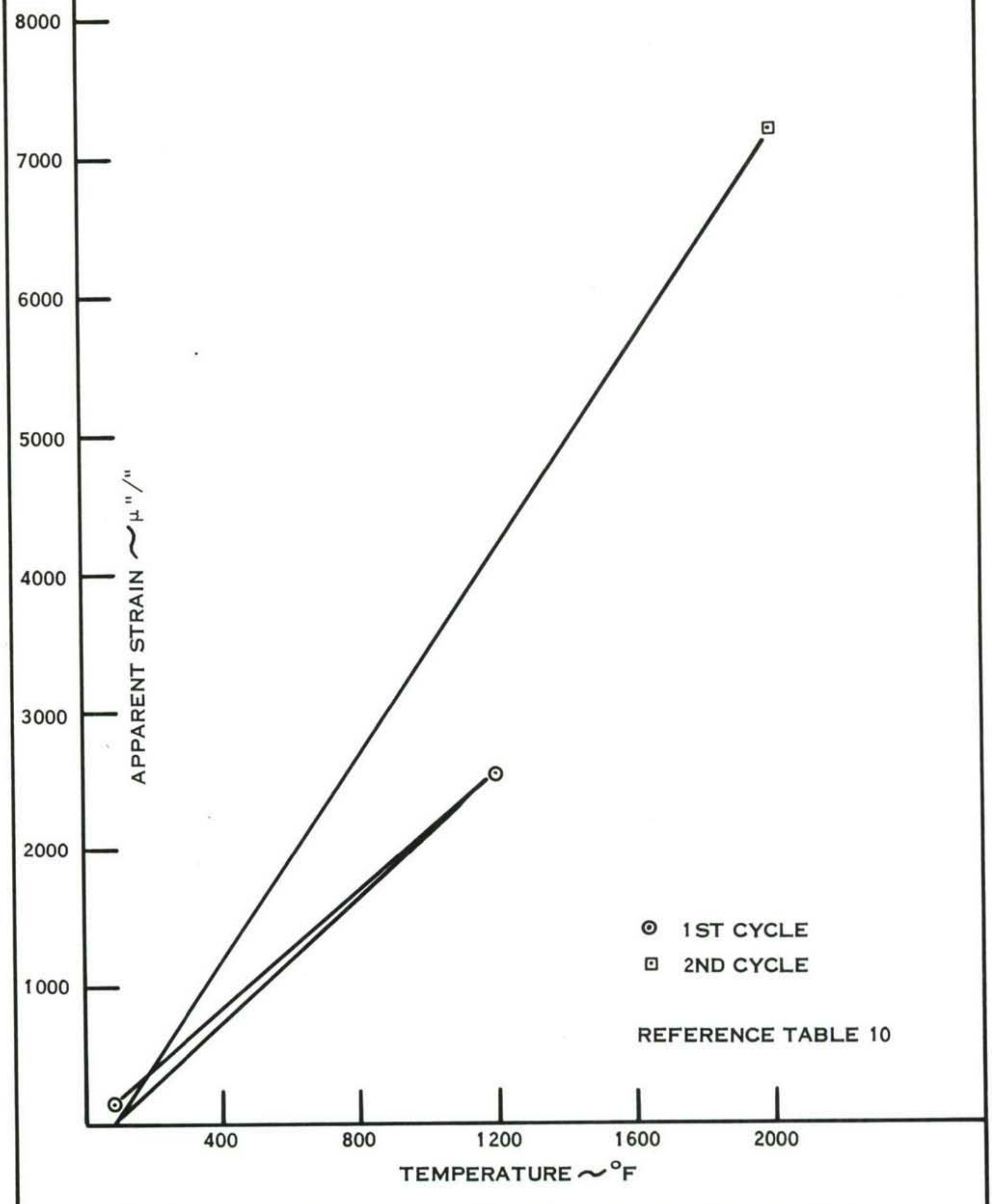


FIGURE 11 APPARENT STRAIN OF A FULL BRIDGE STRAIN GAGE ON HASTELLOY B DURING TRANSIENT HEATING

I. Conclusions

Results obtained from the steady-state and transient heating evaluation tests performed on either Half or Full Bridge strain gages indicated the following:

1. Excellent gage installation to 2000° F., by means of the flame sprayed material.

2. No loss in the strain sensitivity factor due to the addition of the flame sprayed material.

3. Gage resistance and leakage to ground measurements at room temperature were 60 ± .5 ohms and 100 megohms respectively.

4. Gage current capacity at 75° and 2000° F. was not less than 300 milliamps.

5. Negligible drift rate to 1400° F.; however it increased above 1500° F., during its first thermal cycle.

6. Gage stabilized after repeated thermal cycles to 2000°F.

Because of need for strain measurements to 2000° F., further study in the strain and thermal characteristics of a Full Bridge strain gage from 600° to 2000° F., was warranted.

On the basis of previous investigation, an Air Force contract, No. AF 33(657)-11713 was awarded as continuation of the preceding contract.

V. INVESTIGATION OF STRAIN AND THERMAL CHARACTERISTICS OF A FULL BRIDGE STRAIN GAGE (Under Contract No. AF 33(657)-11713)

An Air Force contract, No. AF 33(657)-11713, a continuation of contract No. AF 33(657)-9295, was provided in May 1963 for a study of strain and thermal characteristics of a Full Bridge strain gage from 600° to 2000° F. Specific requirements of this contract were to:

1. Determine coefficient of thermal expansion of all test materials to be used from 600° to 2000° F.

2. Determine the output of an installed gage when subjected to mechanical and thermal loading.

3. Develop a method of measuring experimentally actual deformation over the gage length during the mechanical and thermal loading of a specimen.

Its initial aim was to develop a photographic method of measuring strain at elevated temperatures. This method uses a displacement measuring technique whereby small markings made directly on a surface of a test specimen were photographed during the thermal and mechanical loading. The reproduced displacements both in the axial and lateral axis of the specimen were then measured on an optical comparator under 100 power magnification.

In the illustrated method, Figure 12, an 80 mm lens is used to obtain an image-object ratio of 2. The proper image and object distances were derived as follows:

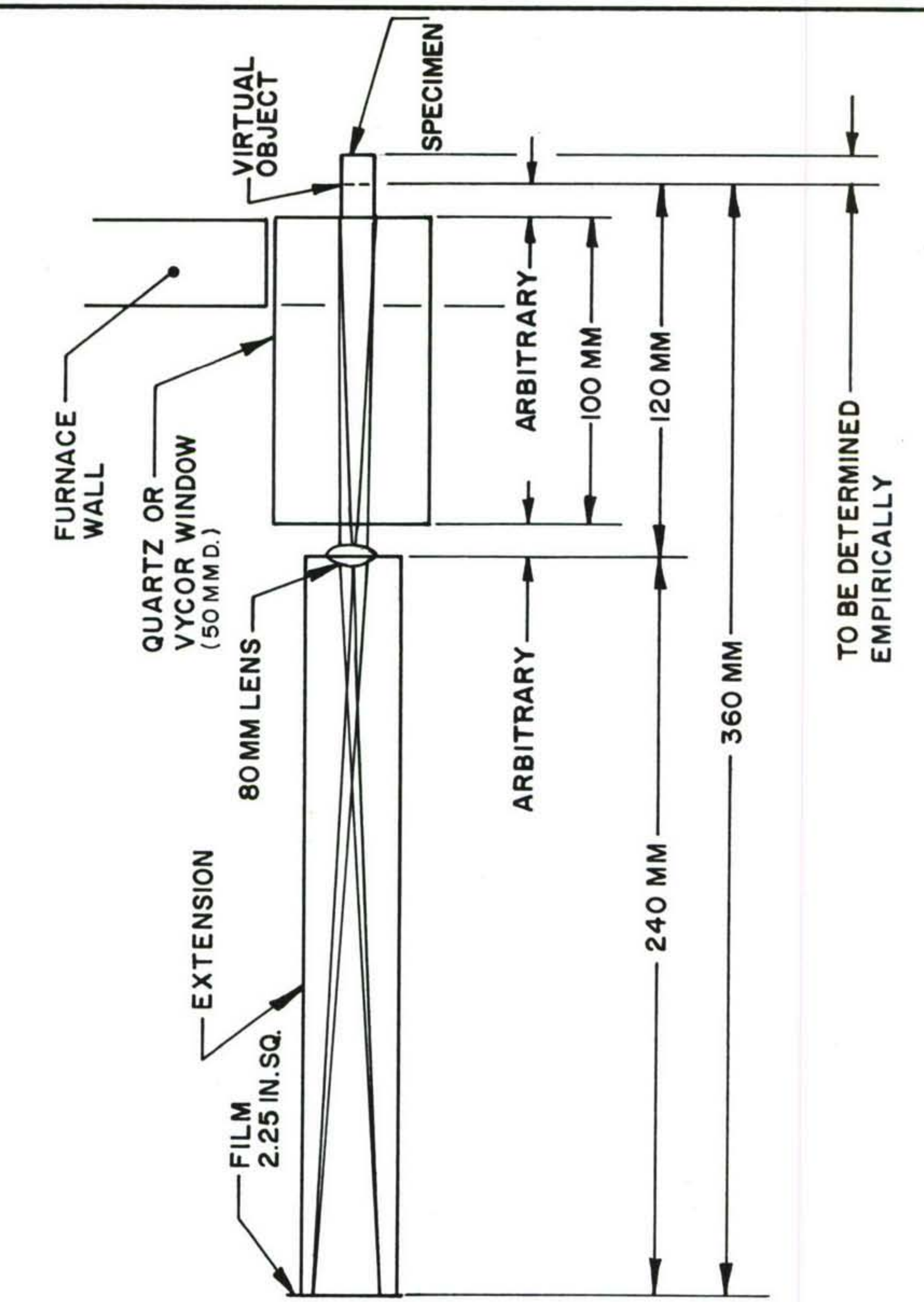


FIGURE 12 – IMAGE–OBJECT RATIO AS USED IN THE PHOTOGRAPHIC STRAIN MEASUREMENT TEST

$$\frac{\text{image size}}{\text{object size}} = \frac{\text{image distance}}{\text{object distance}} = q/p \tag{2}$$

where distances are measured from the center of the lens

$$\frac{1}{q} + \frac{1}{p} = \frac{1}{f} \tag{3}$$

where f is the focal length of the lens

$$\frac{q}{p} = 2 \qquad q = 2p \tag{4}$$

$$\frac{1}{2p} + \frac{1}{p} = \frac{1}{f} \tag{5}$$

$$\frac{3}{2p} = \frac{1}{f} \tag{6}$$

$$p = \frac{3f}{2} \tag{7}$$

$$p = \frac{3\ (80)}{2} = 120 \text{ mm} \tag{8}$$

$$q = 2p = 240 \text{ mm} \tag{9}$$

When two optical flats, such as those formed by the quartz window, are placed between an object and an observer, a virtual image is formed. The virtual image becomes a "virtual object" when a lens is used to project its image. Since the virtual object shown does not coincide with the real object, the lens must be adjusted so as to focus on the virtual object. The image-to-lens distance must always be 3f = 240 mm. The lens to virtual object distance must be $\frac{3f}{2}$ = 120 mm., but the lens-to-real object distance will be slightly greater than 120 mm.

The method used in photographing strain consisted of a Hasselblad Model 500C Reflex camera (80 mm. lens) plus its associated equipment. Initial tests were made at room temperature to become familiar with the photographic equipment and secondly to locate the proper focal distance of the camera lens to the object for the desired image to object size. The tests were performed on a Nimonic test specimen 3/4" diameter by 17" in length. Four markings 0.062" diameter were drilled on the specimen 3/8" apart in the axial and lateral axis. After the specimen was installed in a creep test machine, a 1" Tuckerman optical gage was placed on the specimen directly opposite the four dots. Preliminary

investigations were made using a 2-1/4" x 2-1/4" cut film. A ring light provided the necessary light at 1/1000 sec. shutter speed. Results of the test proved unsatisfactory because of the bending produced by the creep test machine and the instability in using cut film. Figure 13 illustrates the initial photographic strain set up.

A Universal Test machine, 60,000 lbs. maximum loading capacity, was procured from Weidemann Company as a replacement for the creep test machine used in the previous contract.

Since the cut film showed too much variation in the displacement of the markings, a Kodalith ortho glass plate, type 3, 2" x 2" x 0.040" was then used for photographing the dot displacements. A fixture was used to hold the developed glass plates under the optical comparator during displacement measurement.

Kodalith Super developer and Kodak Rapid Fixer were chosen for their excellent ability to reproduce maximum sharpness of the image detail.

The exposure time of the glass plate varied between 15 to 30 seconds with a developing time estimated at 1-1/2 to 2 minutes. The camera was set at a 3 foot focal distance with shutter opening varying between F/16 and F/22 settings. Lighting for the proper exposure of the glass plate became more critical as the gage length on the specimen increased. To reproduce well defined dots the light must be equally distributed over the entire gage length.

In conjunction with the photographic means of measuring strain, a furnace was designed and fabricated for use with the Universal Test machine. The initial heater construction consisted of two coils wound with 10 mil platinum wire around a 1" Vycor tube. Because of the intense heat of the platinum wire, the Vycor glass developed cracks and thus became unsatisfactory for high temperature work. An insulated material of fired Grade A lava was then used as a heater coil and to insulate the ends of the furnace. It was also used for housing a quartz window. A 100% fused silica No. 7940 optical grade blank, 2.020" diameter x 4" thick, was used as the quartz window between the lens and the specimen. To prevent any dispersion of light from the front to the rear face, both surfaces were optically polished to 1/4 wave length.

Center lava pieces were placed over the heater coils to retain heat and provide stability at constant temperatures. The

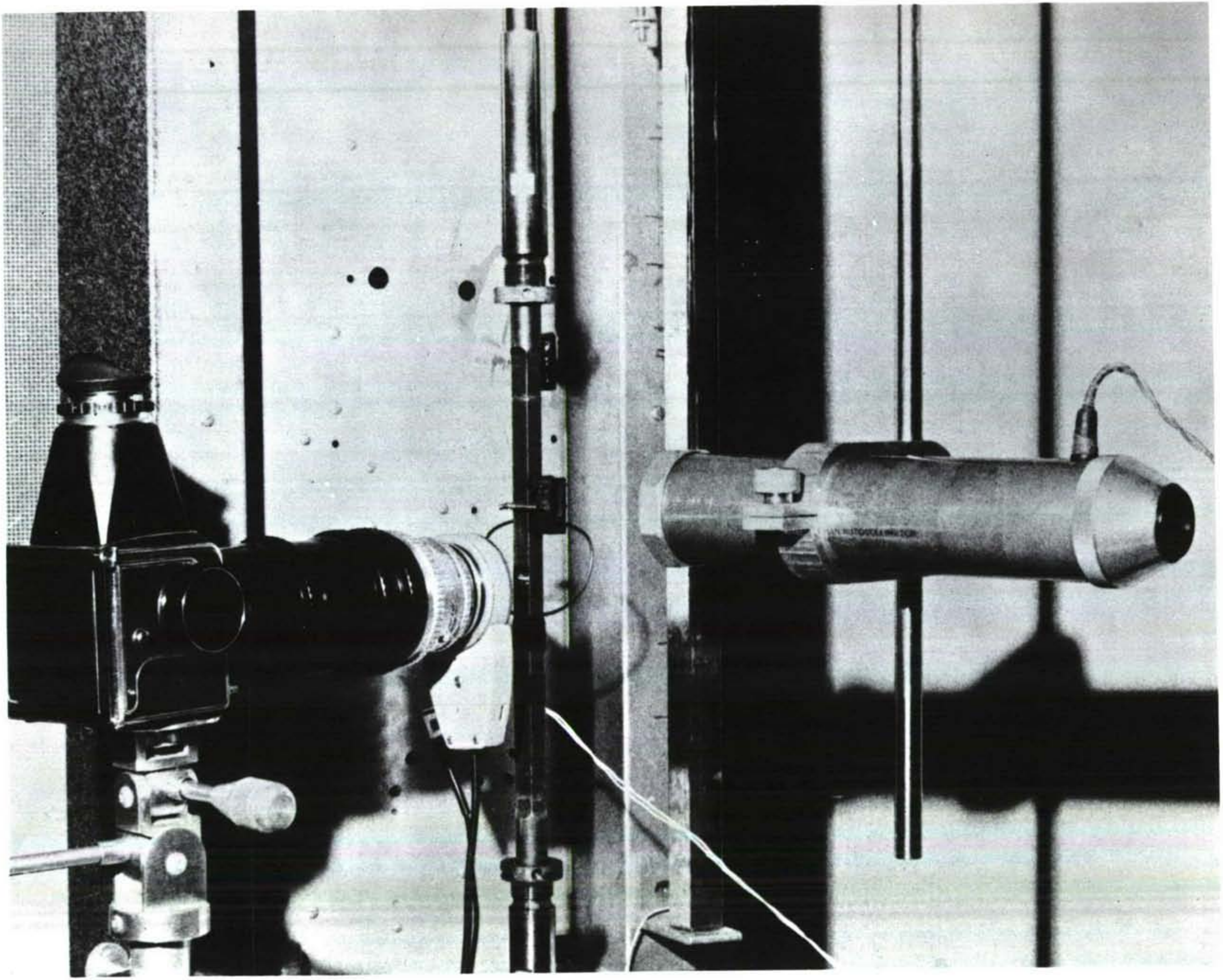


FIGURE 13 VIEW OF THE INITIAL PHOTOGRAPHIC STRAIN SET UP AT 75° F

heater coils were located near the upper and lower ends of the test specimen. A 3-1/2" diameter gold coated Vycor glass was placed over each heater. The specimen under test was placed inside the heater coils, with its center being observed through the quartz window. The initial heater design is illustrated in Figure 14.

A. Room Temperature Tests

1. Creep Test: A creep test was performed at room temperature on two Full Bridge strain gages installed on a Nimonic tensile test specimen 3/4" diameter by 17" long; however, the test section was machined to a 1/2" x 1/2" cross sectional area.

Both gages were initially balanced and their output applied to a strain indicator at a gage factor setting of 4.00.

A constant tensile load of 4800 lbs. was maintained on the specimen for 42 hours. The output of both gages was recorded at the start and at the end of 42 hours. The load was then removed and the resultant strain of both gages at a zero load recorded. Results of the test are shown below:

Load (Lbs.)	Strain Gage 1 Micro "/"	Gage 2 Micro "/"	Remarks
0 (600 lb.preload)	--	--	
4800	1188	1070	Start of test
4800	1118	999	At the end of 42 hours
0	-25	-42	Zero shift at the end of test.

2. Maximum Strain Test: Maximum strain test was performed on a Full Bridge strain gage at room temperature by subjecting the test specimen to its maximum tensile load while recording the gage output.

The first test was performed on an aluminum test specimen, 1/2" x 1/2" x 30". A Full Bridge strain gage was attached to the center of the test specimen with only a thin paper insulation. A 1" Tuckerman optical gage, located in a plane 90 degrees away and adjacent to the gage, was used to indicate the true strain applied to the specimen. The output of the single gage was observed and the data recorded during the axial loading of the specimen.

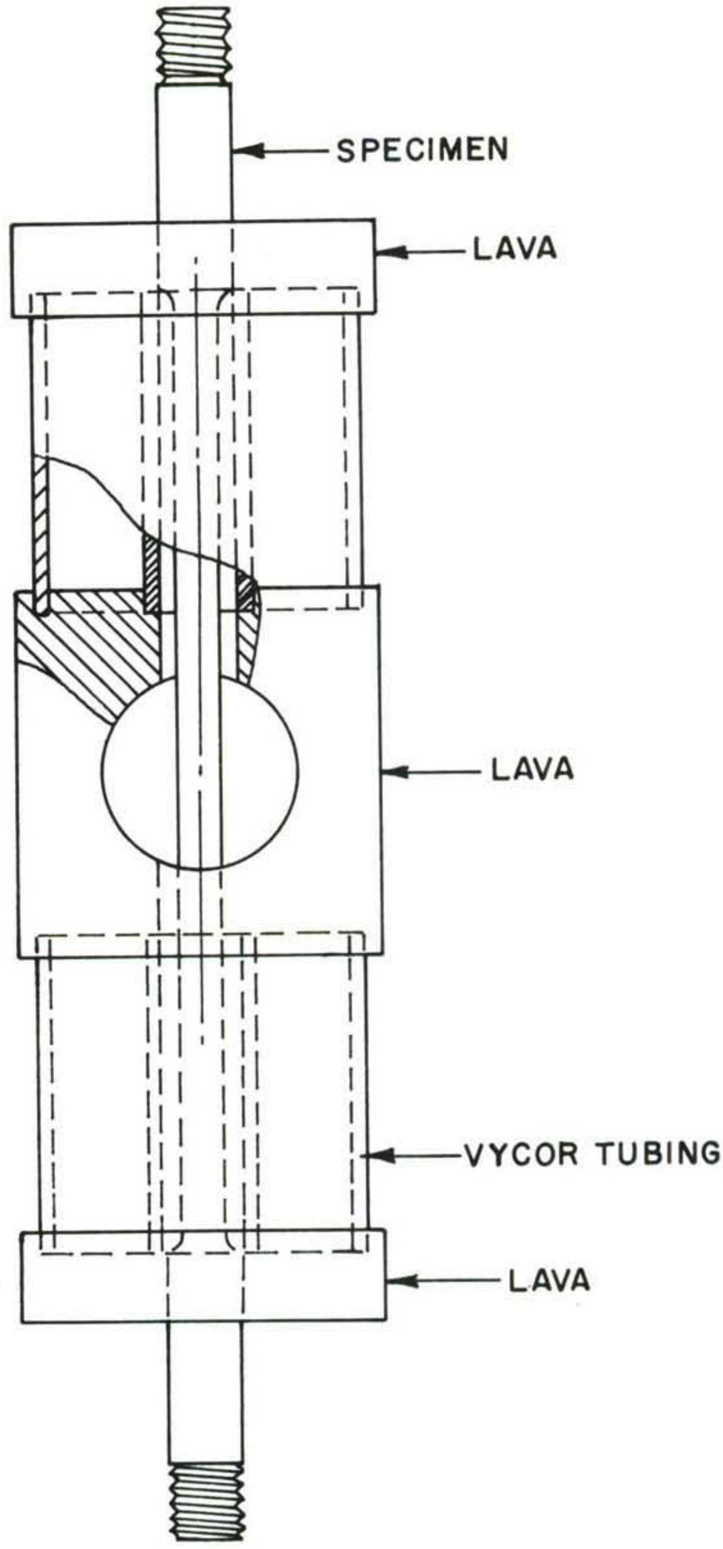


FIGURE 14 — INITIAL HEATER DESIGN

A second test was performed on a test specimen, 0.2" x 0.625" cross sectional area fabricated from a stainless steel type 303 material. After installation of the two Full Bridge strain gages, the test specimen was installed in the tensile test machine. An optical gage was then placed on the test specimen in proximity and 90° away from both gages.

After the strain sensitivity of each gage was determined, the specimen was subjected to an axial load beyond its yield point. The output of both gages and the corresponding load were observed and the data recorded throughout the entire test.

Test results of the maximum strain are indicated in Tables 12 through 14. Stress strain curves for maximum strain performance on the aluminum and stainless steel test specimens are shown in Figure 15.

Gage 2, upon completion of the maximum strain test, was still operable when subjected to normal strain.

TABLE 12

EFFECTS OF MAXIMUM STRAIN ON A FULL BRIDGE STRAIN GAGE AT ROOM TEMPERATURE

Specimen Material: Aluminum - 2024 T-3 (1/2" x 1/2" x 30")
True strain recorded on a Tuckerman optical gage
Strain measurements made on a strain indicator at gage factor 4.00.

K_s the calculated bridge sensitivity factor

$$= \frac{\text{Indicated strain x assumed gage factor}}{\text{true strain}}$$

e Corrected was determined by multiplying the indicated strain reading by $\frac{4.00}{7.19}$
where 4.00 was the assumed gage factor setting on the strain indicator and 7.19 was the calculated average bridge sensitivity factor.

Load Lbs.	Optical Gage Strain μ"/"	Strain μ"/" Gage 1	K_s	e Corrected
0	--	--	--	--
500	208	380	7.30	209
1000	400	700	7.00	385
1500	575	955	6.64	525
2000	774	1460	7.53	803
2500	958	1770	7.40	974
3000	1145	2085	7.28	1147
3500	1345	2460	7.31	1353
4000	1543	2825	7.32	1554
4500	1732	3185	7.35	1752
5000	1920	3525	7.36	1939
5500	2100	3840	7.31	2112
6000	2306	4180	7.25	2299
6500	2498	4515	7.25	2483
7000	2700	4840	7.17	2662
7500	3880	5165	7.17	2841
8000	3095	5490	7.10	3020
8500	3260	5780	7.09	3179
9000	3460	6090	7.04	3350
9500	3660	6380	6.97	3509
10000	3856	6670	6.90	3669
10500	4064	6945	--	3819
-	4136	6990	--	3844
-	4488	7530	--	4142
-	4704	7910	--	4350
-	5200	8800	--	4840
-	632 (Zero Shift)	1248	--	--
			K_s avg. = 7.19	

TABLE 13

STRAIN SENSITIVITY OF TWO FULL BRIDGE STRAIN GAGES AT ROOM TEMPERATURE

Specimen material: Stainless Steel 303 - .125 square inch gage length area

Strain measurements recorded on a strain indicator at gage factor = 4.00.

True strain recorded on the optical gage.

Modulus of elasticity = 29×10^6 psi (tensile load)

Load Lbs.	Optical Gage Micro "/"	Strain Micro "/"		Bridge Sensitivity (K_s)	
		Gage 1	Gage 2	Gage 1	Gage 2
0	0	0	0	--	--
500	128	230	239	7.12	7.45
1000	272	473	467	6.94	6.87
1500	408	705	690	6.90	6.75
2000	532	935	920	7.03	6.90
2500	696	1160	1151	6.67	6.65
3000	832	1378	1398	6.63	6.73
2500	712	1155	1180	6.50	6.67
2000	546	915	950	6.70	6.95
1500	410	675	710	6.58	6.92
1000	266	447	447	6.72	6.72
500	138	212	242	6.14	7.01
0	0	0	0	--	--

Bridge sensitivity factor, $K_s = \dfrac{\text{assumed factor} \times \text{indicated strain}}{\text{true strain}}$

K_s avg. (Gage 1 = 6.72)
(Gage 2 = 6.87)

TABLE 14

EFFECTS OF MAXIMUM STRAIN ON TWO FULL BRIDGE STRAIN GAGES AT ROOM TEMPERATURE

Specimen material: Stainless Steel 303, 0.25 sq.in. gage length

Strain measurements on gage 1 were recorded on a strain indicator at a gage factor = 4.00.

Strain measurements for gage 2 were recorded as millivolt output on an X-Y recording instrument and then converted into strain readings.

Load Lbs.	Optical Gage	Strain Gage 1	Strain Corrected Gage 1	Strain Gage 2	Strain Corrected Gage 2
0	-	-	-	-	-
500	120	219	129	275	160
1000	256	457	270	475	276
1500	400	683	403	710	412
2000	536	922	544	950	551
2500	680	1165	687	1175	682
3000	816	1412	833	1390	806
3500	968	1679	991	1635	948
4000	(beam yielded)	-	-	-	-
	1192	2115	1248	2025	1175
	1232	(gage removed)	-	-	-
4200		2270	1339	2200	1276
4400		2535	1495	2525	1465
4600		3035	1791	2850	1653
4800			2048	3425	1987
5000		4475	2640	4250	2465
			3384	-	-
5200	-	-	-	6350	3683
5400	-	-	-	8650	5017
	-	-	-	17000	9860

Strain corrected for bridge sensitivity factor of 6.72 and 6.87 for gages 1 and 2 respectively.

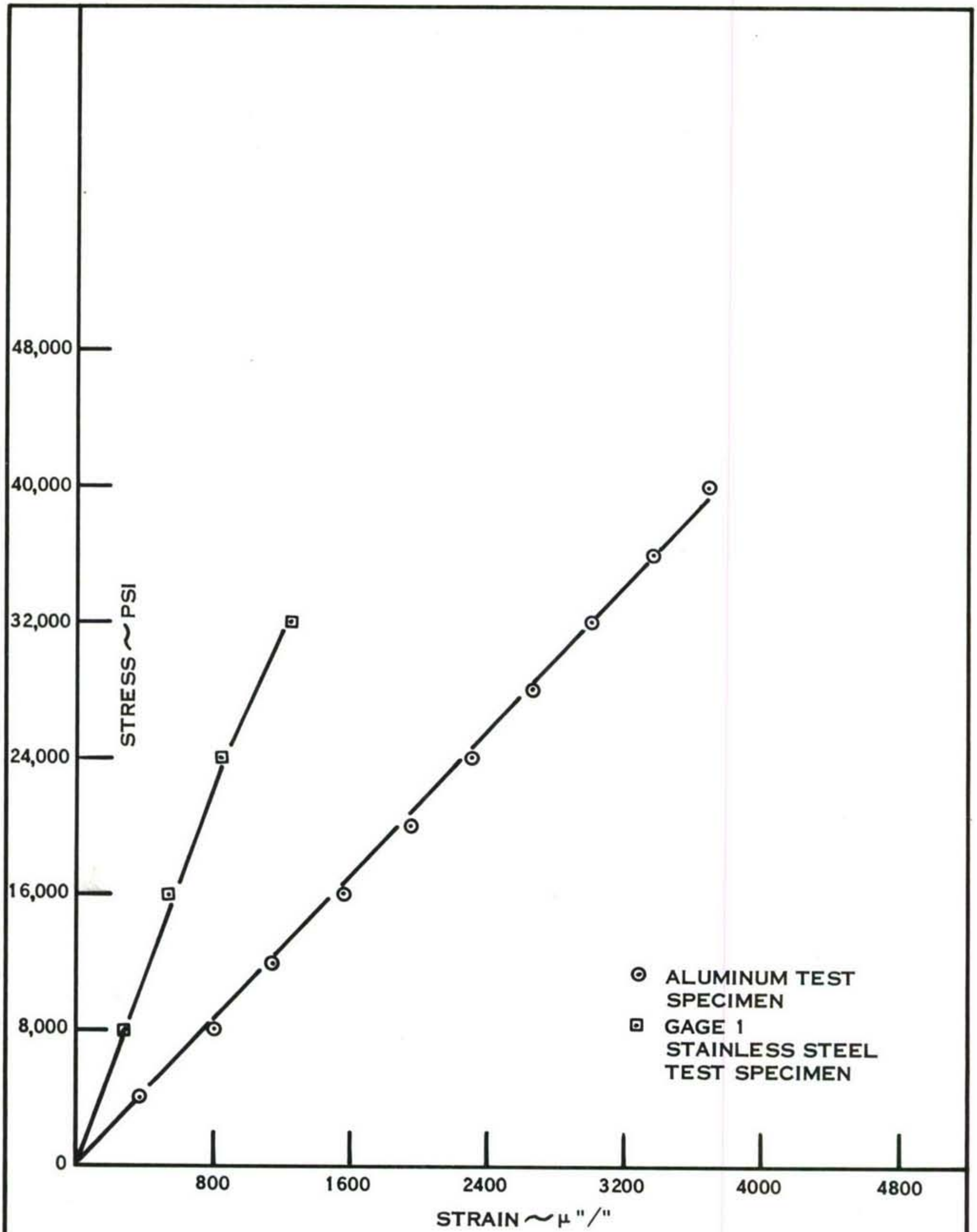


FIGURE 15 GAGE BEHAVIOR AT HIGH STRAIN AT 75°F

3. Transverse Sensitivity Test: Transverse sensitivity of a Full Bridge strain gage was determined by applying a bending load to a test specimen and recording the gage output in the constant moment area, as illustrated in Figure 16.

Transverse sensitivity is defined as the ratio of the indicated strain which would result from a gage mounted 90° from the axis of a uniaxial strain to the indicated strain resultant from a gage mounted parallel to the axis of the same uniaxial strain.

The orientation of gages was as follows:

Gages 1 and 5 are Full Bridge strain gages mounted parallel to the axis of the uniaxial strain.

Gages 2, 3 and 4 are Full Bridge strain gages mounted 90° from the axis of the same uniaxial strain and in the same plane as gages 1 and 5.

Gage 6, four single gages type A-5 electrically connected to form a Full Bridge to monitor bending strain only.

The procedure used in the transverse sensitivity test was as follows: Gages 1, 2 and 4 were initially balanced and the output applied to a strain indicator through a balancing and switching unit while gage 6 output was monitored directly on a separate strain indicator.

The specimen was subjected first to a bending load from 0 to 6000 lbs. The output of the four gages were recorded in 1000 lb. increments. The indicated strain was recorded at a gage factor setting of 4.00 for gages 1, 2 and 4 and a gage factor setting of 2.02 for gage 6. The resultant data is tabulated below:

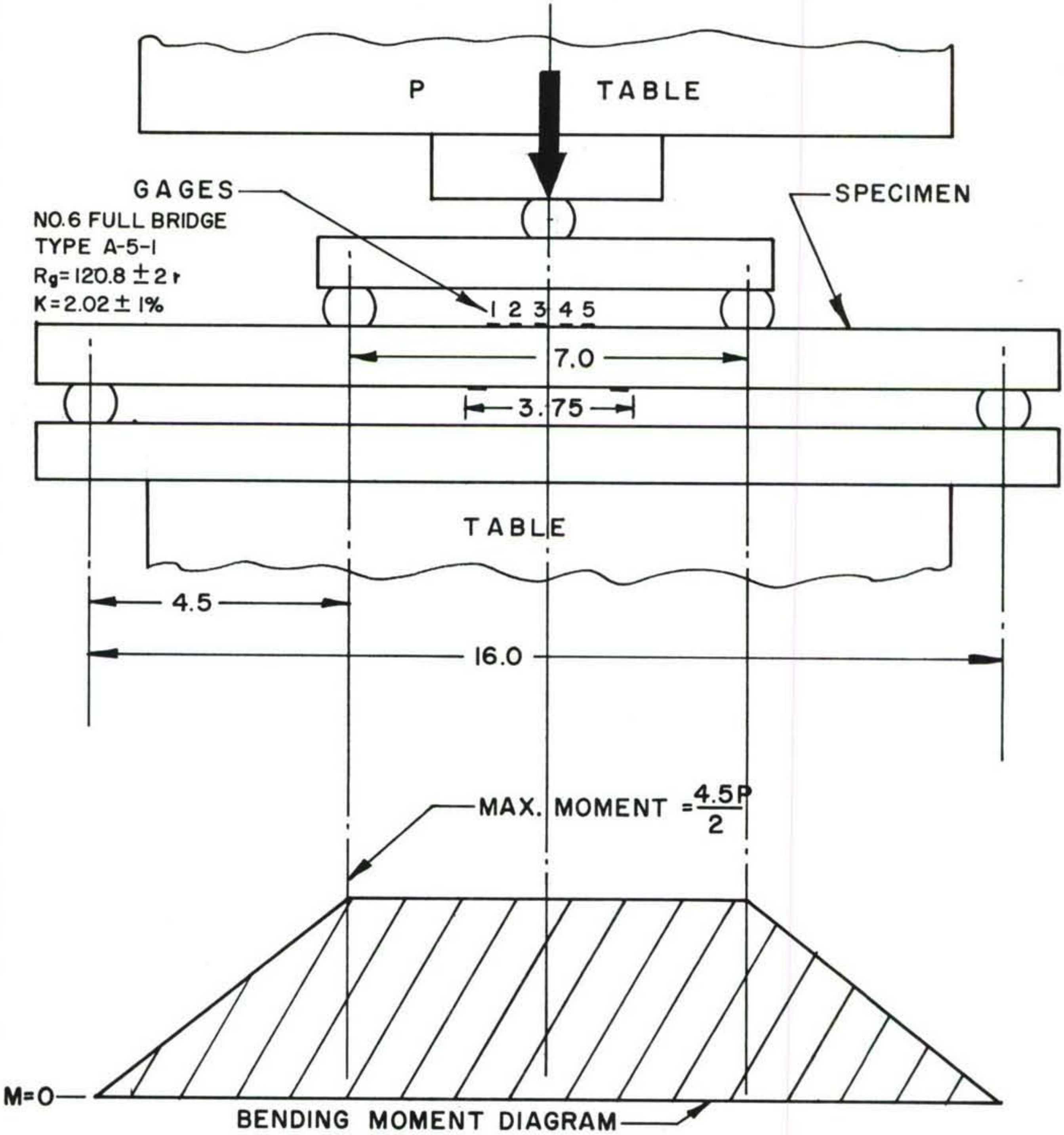


FIGURE 16 - SET UP FOR TRANSVERSE SENSITIVITY TEST ON A FULL BRIDGE STRAIN GAGE

Load Lbs.	Stress Psi	Calc. Strain	True Strain	Indicated Strain Gage: 1	2	4	K_s
0	-	-	-	-	-	-	-
1000	4,500	155	150	240	70	65	6.40
2000	9,000	310	300	475	135	125	6.33
3000	13,500	465	450	760	200	180	6.76
4000	18,000	620	600	1000	265	240	6.67
5000	22,500	775	750	1250	300	295	6.67
6000	27,000	930	900	1495	390	355	6.64

Avg. K_s = 6.58.

The calculated strain was determined by the following equations:

$$S = 4.5\ P \text{ and} \tag{10}$$

$$e = {}^{S}/_{E_M} \tag{11}$$

where S is the calculated stress in psi

P is the applied load in lbs.

e is the calculated strain in micro inches per inch

E_M is the modulus of elasticity for the material used which is equal to 29×10^6 psi

The true strain was obtained by dividing the indicated strain of gage 6 by four.

The bridge sensitivity factor K_s of gage 1 was determined as follows:

$$K_s = \frac{\text{Indicated strain (gage 1) x assumed gage factor (4.00)}}{\text{true strain}}$$

The strain indicator was then preset at 1/2 the average bridge sensitivity factor where

K_s avg. = 6.58
1/2 K_s avg. = 3.29

and the output of gages 1, 2 and 4 observed and recorded while subjecting the test specimen to an additional bending load from 0 to 6000 lbs.

The indicated strain was then corrected for the bridge sensitivity factor (6.58) by multiplying the resultant output of gages 1, 2 and 4 by 0.50. Results of this test are shown below:

	Indicated Strain 1/2 K_s Avg. 3.29			Corrected Strain K_s = 6.58			Transverse Sensitivity (F_T) $\left(\frac{E_T}{E_a}\right)$	
Load	Gages			Gages			Gages	
Lbs.	1	2	4	1 (E_a)	2 (E_T)	4 (E_T)	2	4
0	-	-	-	-	-	-	-	-
1000	275	80	75	138	40	38	.289	.275
2000	560	155	140	280	77.5	70	.276	.250
3000	900	230	215	450	115	107.5	.255	.239
4000	1205	310	285	602.5	155	142.5	.257	.237
5000	1490	390	355	745	195	177.5	.262	.238
6000	1775	470	420	887.5	235	210	.265	.236

The axial strain (E_a) recorded by gage 1, and the transverse strain recorded by gages 2 and 4 are shown above under the column heading "Corrected Strain".

Transverse sensitivity for gages 2 and 4 are shown under the column heading "Transverse Sensitivity" above. The resultant load-strain curves for the true strain and transverse sensitivity of gages No. 2 and No. 4 are shown in Figure 17.

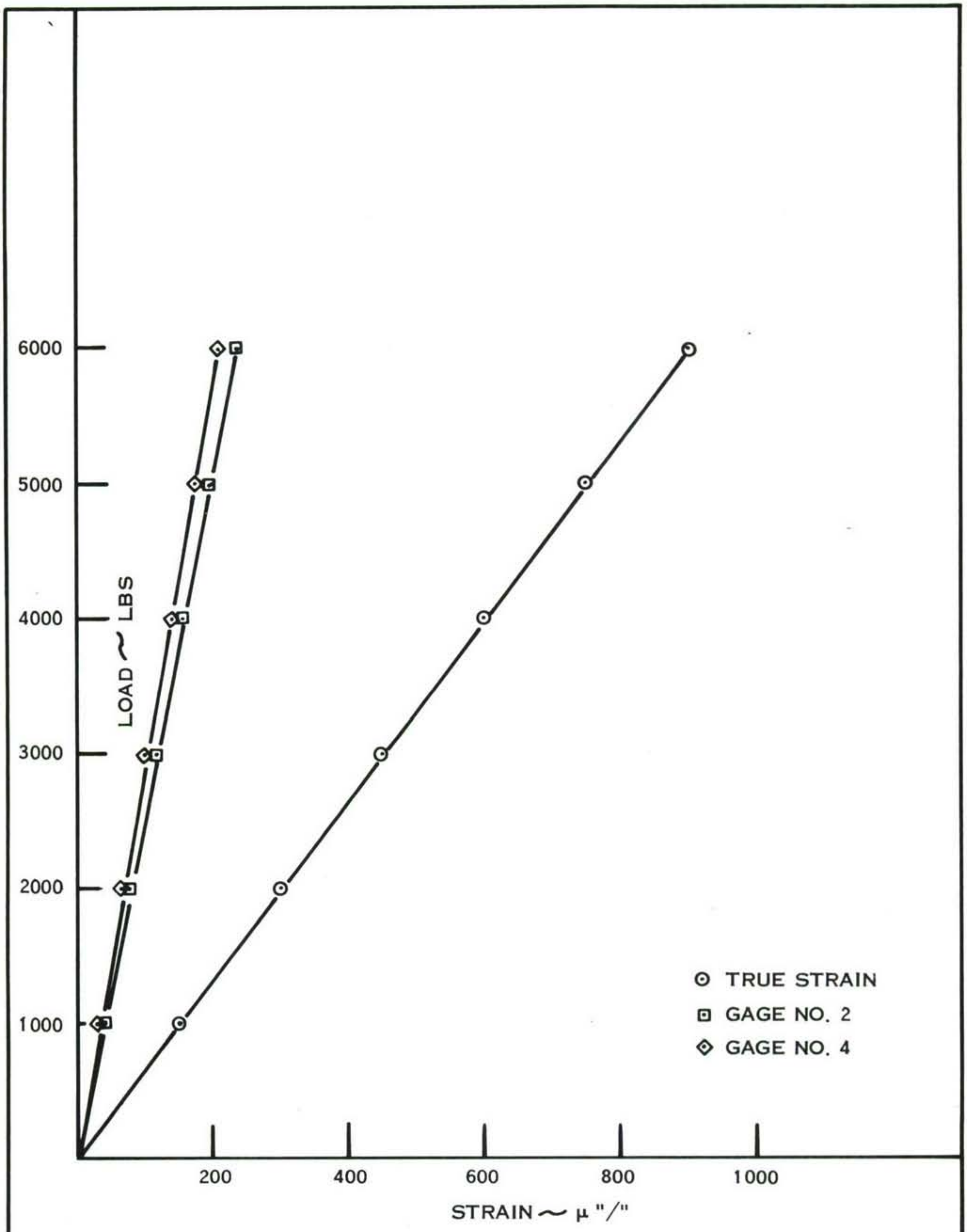


FIGURE 17 TRANSVERSE SENSITIVITY OF TWO FULL BRIDGE STRAIN GAGES

4. Strain Sensitivity and Effects of Bridge Voltage on Strain Sensitivity: Strain sensitivity and the effects of bridge voltage on strain sensitivity were performed at room temperature on Full Bridge strain gages installed on Nickel and Inconel X-750 tensile test specimens.

Two Full Bridge strain gages were installed on the opposite side of each test specimen. They were centrally located on a 1/2" x 1/2" cross sectional area. After the installation of each test specimen in the tensile test machine, a 2" Tuckerman optical gage was aligned on the side adjacent and in proximity of both gages.

Both bridges were then initially balanced by means of the 12-channel balance and switch unit and their output monitored on a strain indicator at a gage factor setting of 4.00. An axial load was then applied to the specimen from 0 to 8000 lbs., in 1000 lb. increments for three repeatable cycles. At each point the Tuckerman optical gage and both strain gages were monitored and the data tabulated.

The effects of bridge voltage on strain sensitivity were determined by subjecting the instrumented test specimen to an axial load cycle from 0 to 8000 lbs.

Each gage was initially balanced at each applied input voltage and its output applied to both axes of the X-Y recording instrument so that equal voltage existed on both axes. During the continuous loading from 0 to 8000 lbs., each gage output was individually recorded at various bridge inputs.

In order to determine the non-linearity of the gage, the deflection in both axes was easily distinguished for any erratic behavior of the gage; however, if only one axis was used then the reproduced straight line would not be sufficient to detect any non-linearity in the gage response.

At a bridge input of either 4 or 5 volts D.C., the millivolt output from each gage was recorded separately on the Y-axis over load range of 0 to 8000 lbs. The load was marked manually by repositioning the zero control on the X-axis for each 1000 lb. increment.

A typical data sheet used in tabulating strain sensitivity of a Full Bridge strain gage is shown in Figure 18.

A leakage to ground and the bridge resistance were also measured for each gage.

TEST ______________________________

DATE ______________ OPERATOR ______________

GAGE FACTOR SETTING ______________ R CAL EQUIV. ______________

BRIDGE VOLTAGE ______________

LOAD (LBS.)	CYCLE 1			CYCLE 2		CYCLE 3		BRIDGE SENSITIVITY FACTOR
	STRAIN	MV	TRUE STRAIN	STRAIN	MV	STRAIN	MV	
0								
1000								
2000								
3000								
4000								
5000								
6000								
7000								
8000								
7000								
6000								
5000								
4000								
3000								
2000								
1000								
0								

FIGURE 18 TYPICAL DATA SHEET USED IN RECORDING STRAIN SENSITIVITY MEASUREMENTS

Results and Conclusions of Tests at 75° F.

Results of the strain sensitivity and the effects of bridge voltage on strain sensitivity on two Full Bridge strain gages installed on Nickel test specimen are shown in Table 15.

Two Full Bridge strain gages 1 and 2 were installed on a Nickel test specimen. They were centrally located on a 1/2" x 1/2" cross sectional area of a 3/4" diameter by 17" length test specimen. The gages were installed on the opposite sides of the specimen. A two inch Tuckerman optical gage was aligned on the side adjacent and in a plane 90° away from both gages.

Bridge sensitivity factor, shown in Table 15, was calculated as follows:

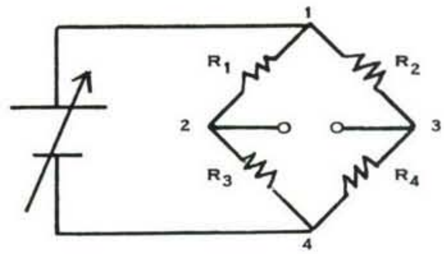
$$K_S = \frac{\text{assumed gage factor x indicated strain}}{\text{true strain}} \qquad (1)$$

Stress-strain relationship and the effects of bridge voltage on strain sensitivity for the gages are shown in Figures 19 through 22.

The results of the strain sensitivity test on gages installed on an Inconel X-750 test specimen are indicated in Table 16. These gages were used in the final evaluation of the Full Bridge strain gage at elevated temperatures.

Strain sensitivity and effects of bridge voltage on strain sensitivity tests at room temperature were completed. Resultant data is expressed in Table 16 and the stress-strain curves illustrated in Figures 23 through 26. The plots expressed in these figures indicate a linear gage output and show no deviation between the gage response and the optical gage output. However, there is some loss in the gage response by increasing the bridge voltage.

Gage and leakage resistance measured at room temperature on gages installed on an Inconel X-750 specimen is indicated as follows:



Resistance (ohms)	R_1	R_2	R_3	R_4	(Power) R_{1-4}	(Signal) R_{2-3}
Specimen No. 1						
Gage 1	51.05	50.14	49.95	51.17	65.49	65.32
Gage 2	49.83	49.64	49.17	50.08	64.35	64.07
Specimen No. 2						
Gage 1	49.62	--	--	49.93	65.45	65.21
Gage 2	50.47	--	--	51.12	64.63	64.37

The leakage to ground resistance measured at room temperature between gage and specimen was approximately 1000 megohms. Insulation voltage check measured between the strain wires was approximately 1400 volts and 1800 volts between strain wire and the specimen.

TABLE 15

STRAIN SENSITIVITY AND EFFECTS OF BRIDGE VOLTAGE ON STRAIN SENSITIVITY AT ROOM TEMPERATURE ON TWO FULL BRIDGE STRAIN GAGES AND AN OPTICAL GAGE WHEN INSTALLED ON A NICKEL TEST SPECIMEN.

1. Strain recorded in micro-inches per inch on a strain indicator at gage factor = 4.00.

2. Tabulated strain measurements are the average of three repeatable readings.

3. True strain readings were observed on a Tuckerman Optical Gage.

Load	Strain			Corrected Strain		Bridge Sensitivity Factor K_S	
Lbs.	Optical	Gage 1	Gage 2	Gage 1	Gage 2	Gage 1	Gage 2
0	-	-	-	-	-	-	-
1000	128	215	216	131	123	6.65	7.03
2000	248	420	445	256	254	6.85	7.30
3000	384	626	665	382	379	6.56	6.98
4000	512	835	889	509	507	6.55	6.97
5000	640	1036	1109	632	632	6.48	6.97
6000	768	1233	1327	752	756	6.43	6.93
7000	888	1445	1560	881	889	6.48	7.01
8000	1024	1659	1775	1012	1012	6.47	6.96
7000	888	1450	1560	884	889	-	-
6000	768	1241	1340	757	764	-	-
5000	640	1026	1116	626	636	-	-
4000	512	815	892	497	508	-	-
3000	384	615	670	375	382	-	-
2000	248	438	463	267	264	-	-
1000	128	215	225	132	128	-	-
0	0	0	0	0	0	-	-
				K_S average		6.55	7.01

Table 15 (Continued)

Load Lbs.	Millivolt Output at 5 Volts D.C. Bridge Input 1	2
0	-	-
1000	1.10	1.12
2000	2.13	2.25
3000	3.10	3.35
4000	4.15	4.28
5000	5.15	5.30
6000	6.10	6.30
7000	7.05	7.20
8000	8.05	8.20
7000	7.07	7.30
6000	6.02	6.35
5000	5.00	5.45
4000	4.00	4.42
3000	3.03	3.35
2000	2.10	2.30
1000	1.10	1.15
0	0	0

Effects of bridge voltage on strain sensitivity is shown below:

Bridge Input Voltage Volts D.C.	Millivolt Output at 8000 lb. Load Gages: 1	2
1	1.70	1.80
3	5.15	5.30
5	8.05	8.20
8	13.00	13.20

The following R cal equivalent was obtained for each gage by shunting 30,000 ohms across each of the active arms and recording the average indicated strain in micro inches per inch at a gage factor setting of 4.00.

Gage 1 445 micro inches per inch
Gage 2 485 " " " "

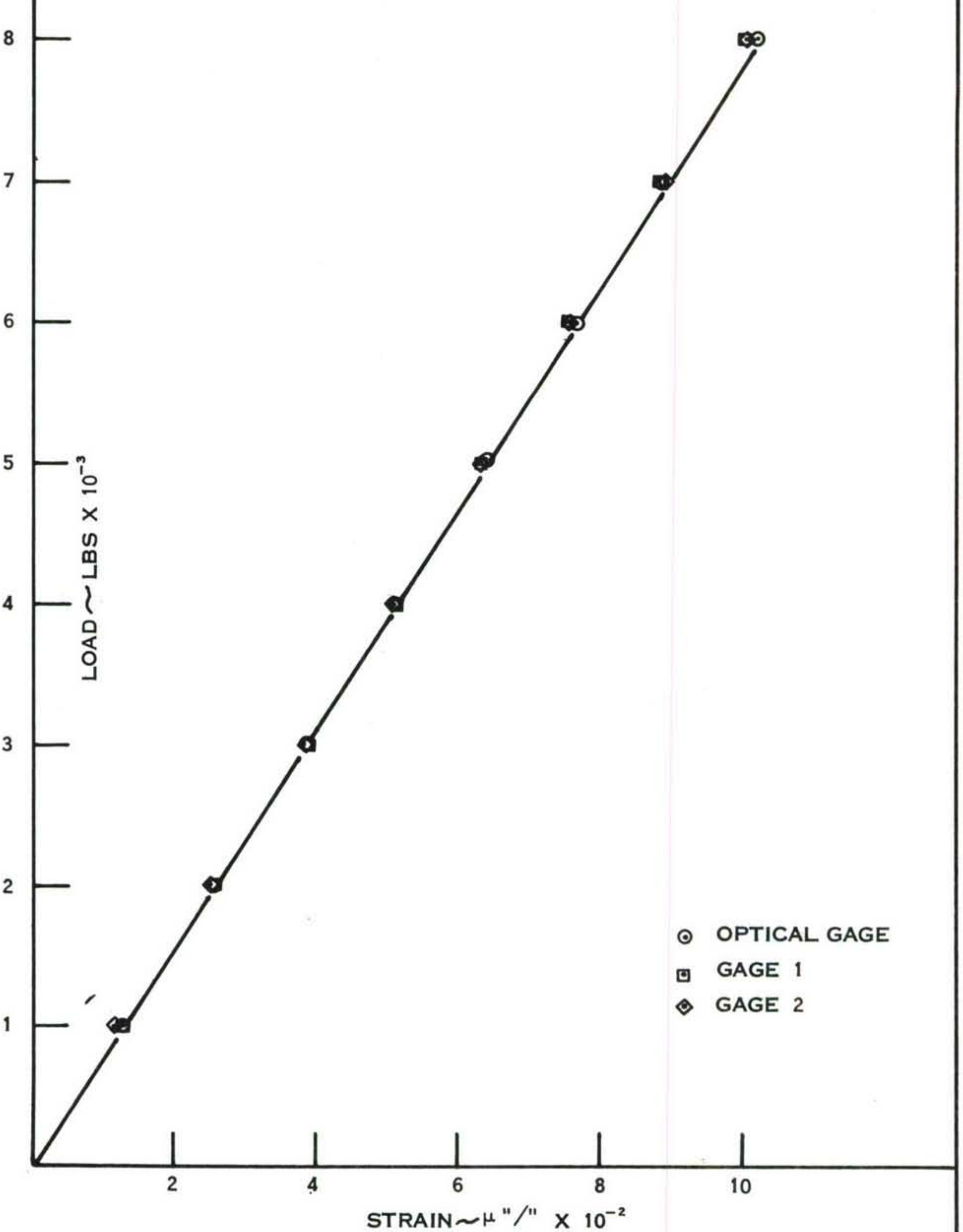


FIGURE 19 STRAIN SENSITIVITY OF TWO FULL BRIDGE STRAIN GAGES AND THE OPTICAL GAGE AT 75°F ON NICKEL

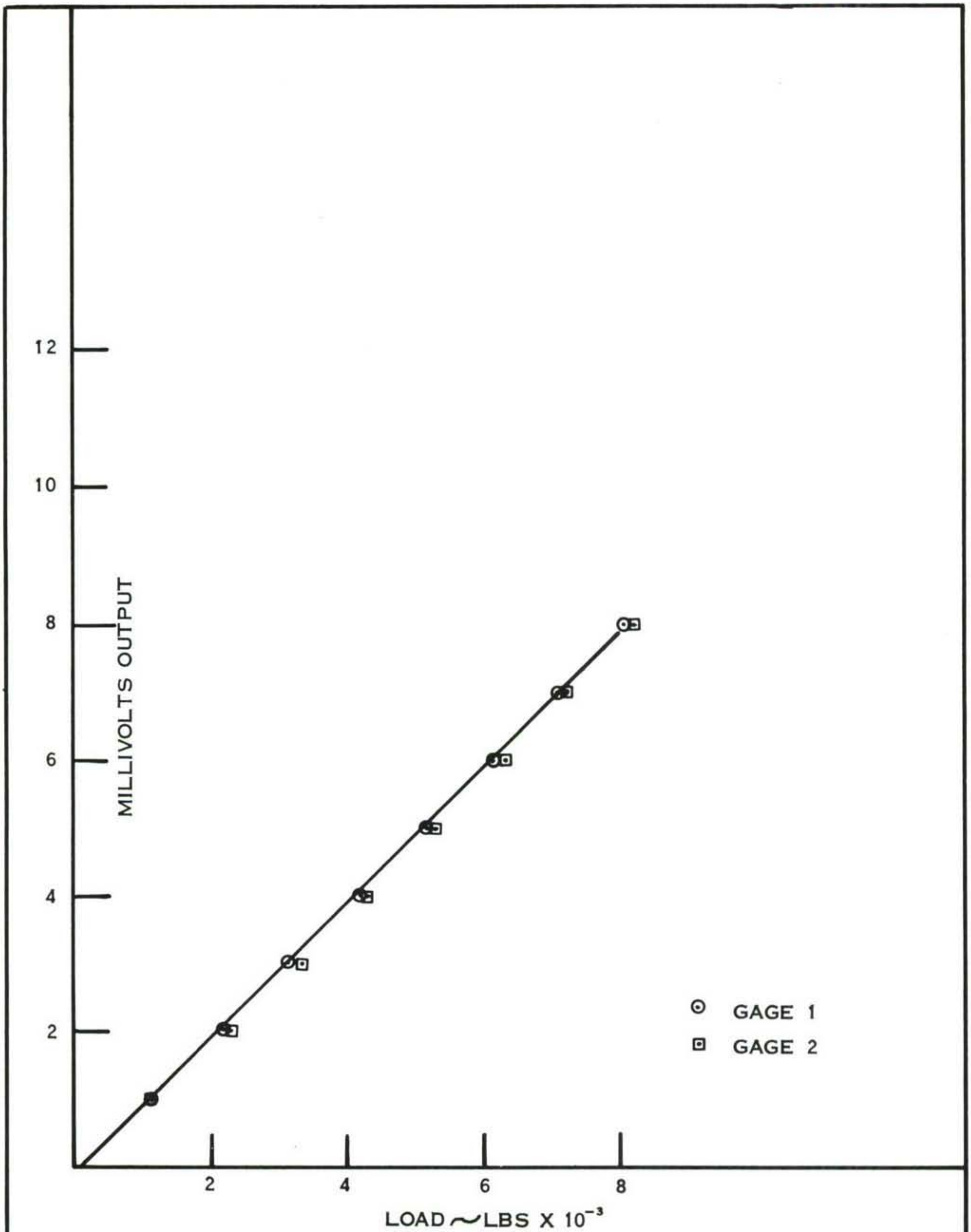


FIGURE 20 BRIDGE OUTPUT OF TWO FULL BRIDGE STRAIN GAGES WITH 5 VOLTS D.C. APPLIED TO THE BRIDGE AT 75°F ON NICKEL

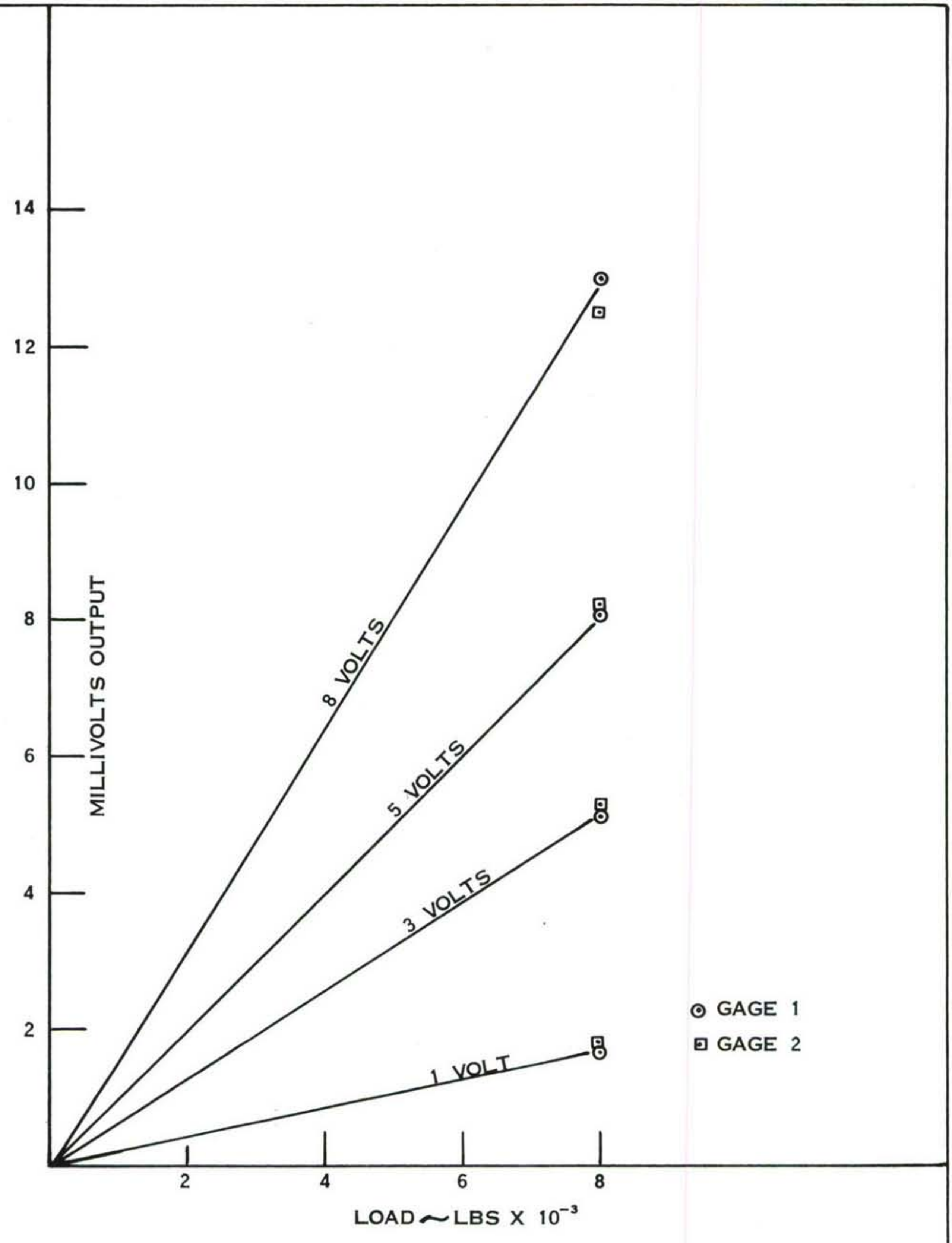


FIGURE 21 EFFECTS OF BRIDGE VOLTAGE ON STRAIN SENSITIVITY OF TWO FULL BRIDGE STRAIN GAGES AT 75°F ON NICKEL

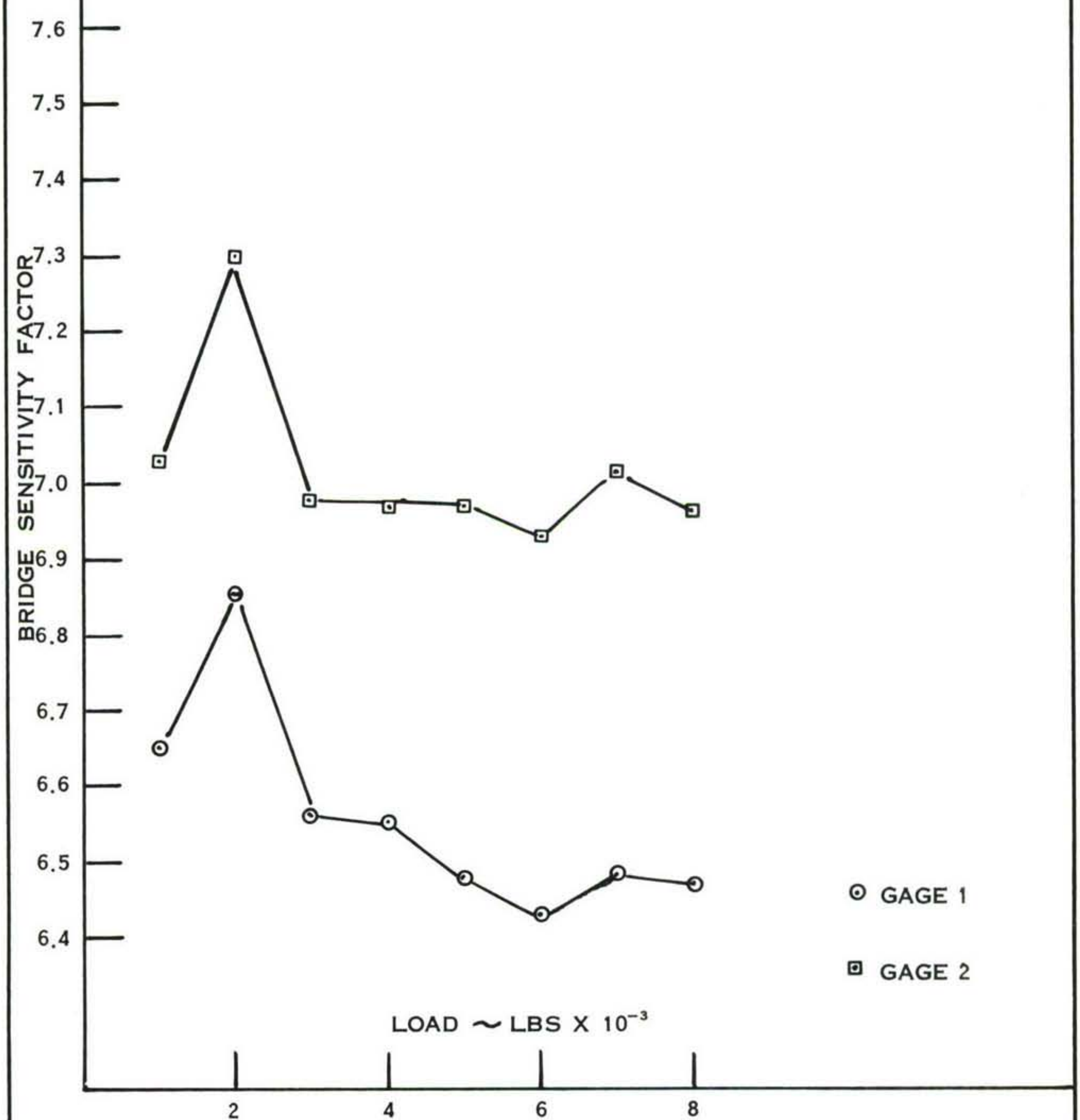


FIGURE 22 EFFECTS OF LOAD ON BRIDGE SENSITIVITY FACTOR OF TWO FULL BRIDGE STRAIN GAGES AT 75°F ON NICKEL

TABLE 16

STRAIN SENSITIVITY AND EFFECTS OF BRIDGE VOLTAGE ON STRAIN SENSITIVITY AT ROOM TEMPERATURE ON THREE FULL BRIDGE STRAIN GAGES AND THE OPTICAL GAGE WHEN INSTALLED ON AN INCONEL X-750 TEST SPECIMEN

Specimen: Inconel X-750 machined
- Specimen No. 1- gage length cross sectional area - 0.2774 sq. in.
- Specimen No. 2 - gage length cross sectional area - 0.2831 sq. in.

Remarks:

1. Strain measurements observed on a strain indicator at gage factor = 4.00.

2. Tabulated strain measurements are the average of three repeatable cycles.

3. True strain readings were observed directly on an optical gage.

Load	Optical Gage Specimens		Strain Measurement Specimen 1		Specimen 2			
Lbs.	1	2	Gage 2	Correc. for K_s= 6.85	Gage 1	Correc. for K_s= 6.33	Gage 2	Correc. for K_s= 6.47
0	-	-	-	-	-	-	-	-
1000	104	120	175	101	170	107	190	118
2000	208	232	365	212	355	224	370	229
3000	328	344	555	322	535	337	560	347
4000	440	456	745	432	715	450	745	462
5000	544	568	940	545	900	567	930	577
6000	664	680	1130	655	1080	680	1110	688
7000	776	784	1325	769	1260	794	1285	797
8000	880	912	1520	882	1440	907	1465	908
7000	776	800	1345	780	1270	800	1290	800
6000	664	688	1145	664	1085	684	1110	688
5000	536	576	950	551	900	567	925	574
4000	432	464	760	441	715	450	745	462
3000	320	344	565	328	535	337	565	350
2000	208	232	370	215	350	221	375	233
1000	100	112	185	107	170	107	200	124
0	-	-	5	-	-	-	-	-

Table 16 (Continued)

Load Lbs.	Output (Millivolt) at 4v DC Bridge Input Spec.1 Gage 2	Specimen 2 Gage 1	Specimen 2 Gage 2		Bridge Sensitivity (K_s) Specimen 1 Gage 2	Specimen 2 Gage 1	Specimen 2 Gage 2
0	-	-	-		-	-	-
1000	.70	.68	.77		6.73	-	6.50
2000	1.40	1.40	1.50		7.03	6.12	6.37
3000	2.14	2.10	2.15		6.78	6.22	6.51
4000	2.80	2.85	2.95		6.78	6.38	6.54
5000	3.62	3.55	3.70		6.91	6.34	6.55
6000	4.32	4.22	4.40		6.82	6.35	6.53
7000	5.10	4.95	5.05		6.84	6.30	6.56
8000	5.80	5.60	5.72		6.95	6.37	6.43
				Average	6.85	6.33	6.47

Load Lbs.	Specimen 1 Bridge Input Volts DC	Specimen 1 Gage 2 mv.	Specimen 2 Gage 1 mv.	Specimen 2 Gage 2 mv.
8000	2	3.00	3.30	3.33
8000	4	5.80	5.60	5.63
8000	6	8.00	8.10	8.16
8000	8	10.00	10.00	10.20

Gage 1, installed on specimen 1, had failed prior to the strain sensitivity test.

An Rcal equivalent was obtained by shunting 30,000 ohms across each of the active arms and recording their average strain in micro inches per inch as indicated on a strain indicator at a gage factor of 4.00.

Specimen 1 Gage 2	Specimen 2 Gage 1	Specimen 2 Gage 2	
515	525	525	Micro-Inches per Inch

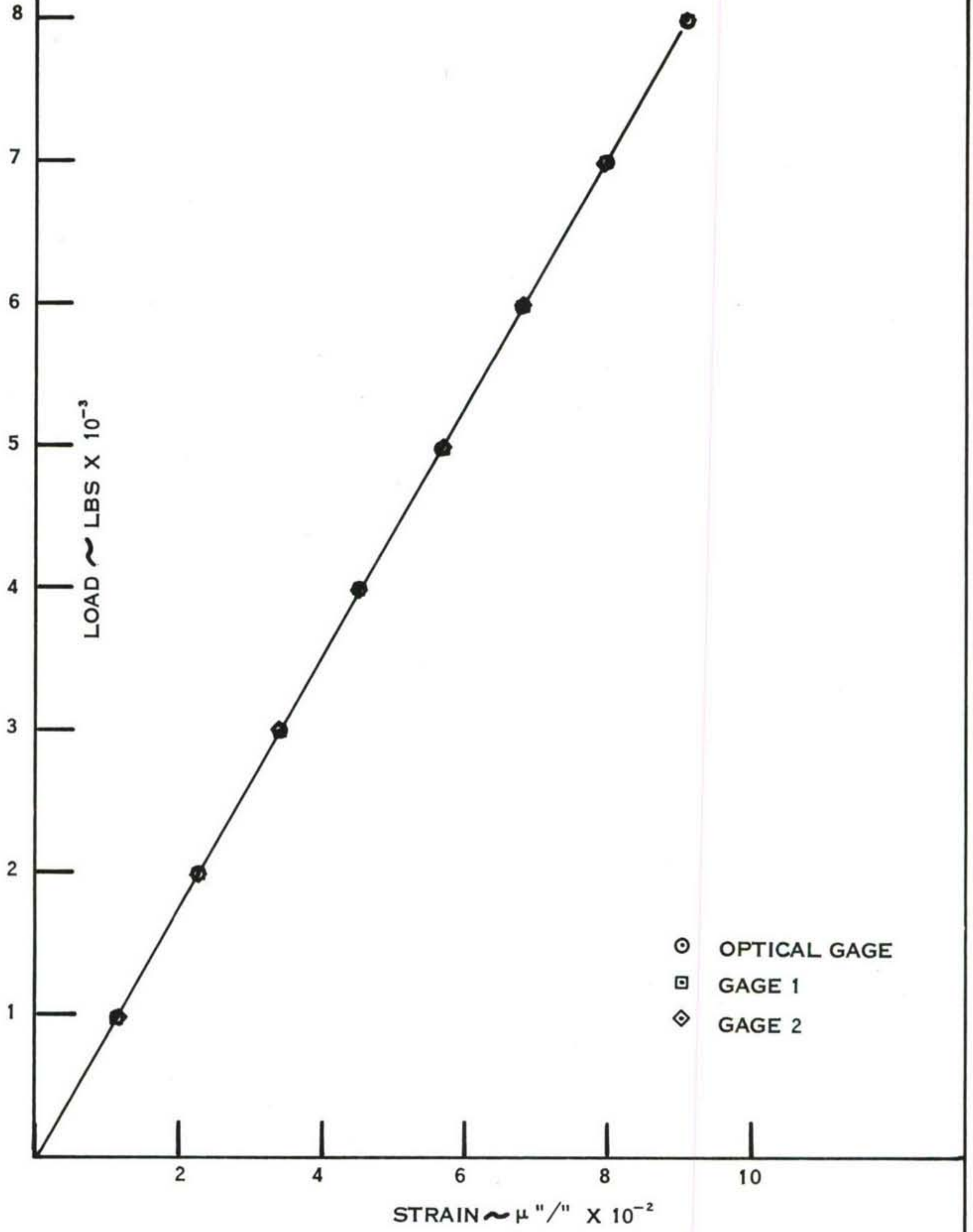


FIGURE 23 STRAIN SENSITIVITY OF TWO FULL BRIDGE STRAIN GAGES AND THE OPTICAL GAGE AT 75°F ON INCONEL X–750, SPECIMEN NO. 2

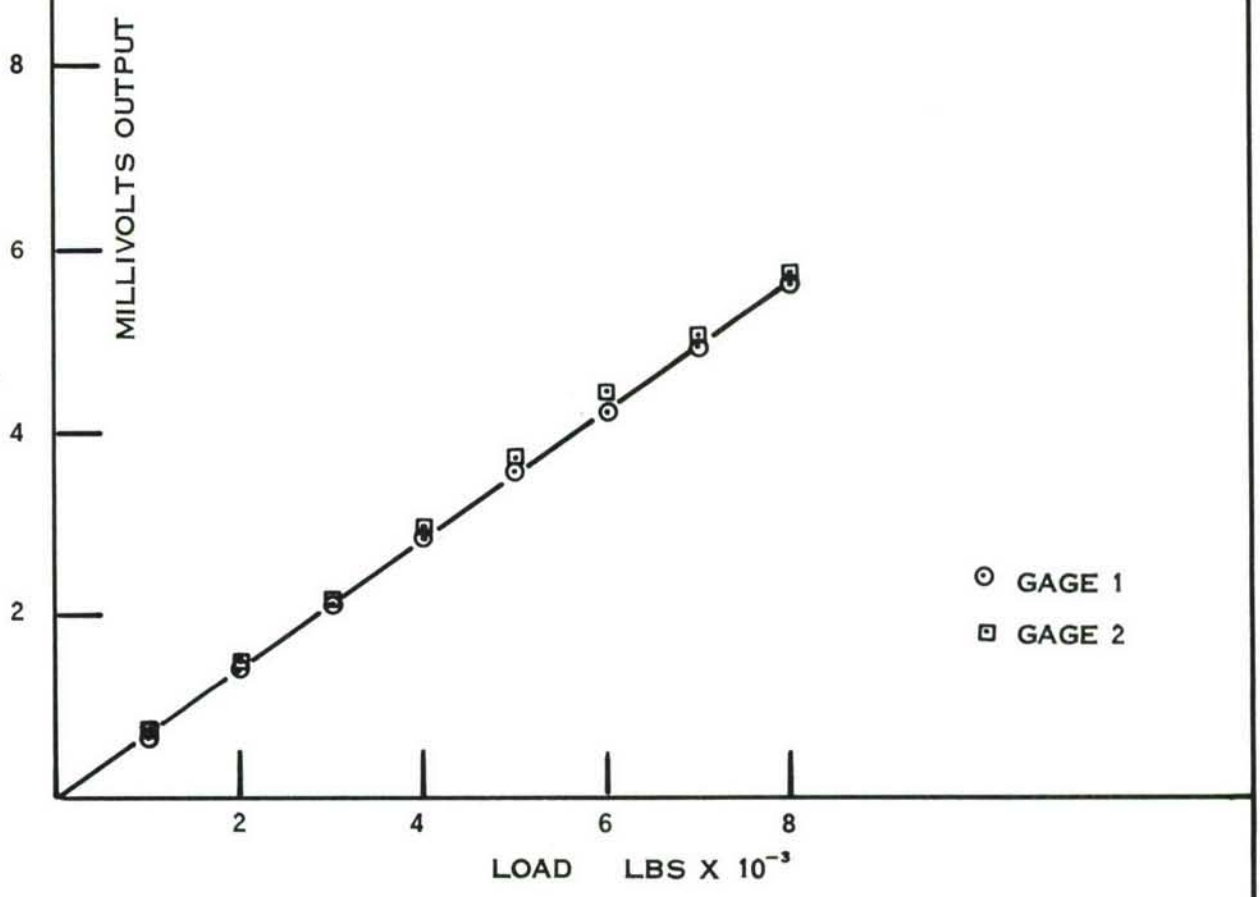


FIGURE 24 BRIDGE OUTPUT OF TWO FULL BRIDGE STRAIN GAGES WITH 4 VOLTS D.C. APPLIED TO THE BRIDGE AT 75°F ON INCONEL X–750, SPECIMEN NO. 2

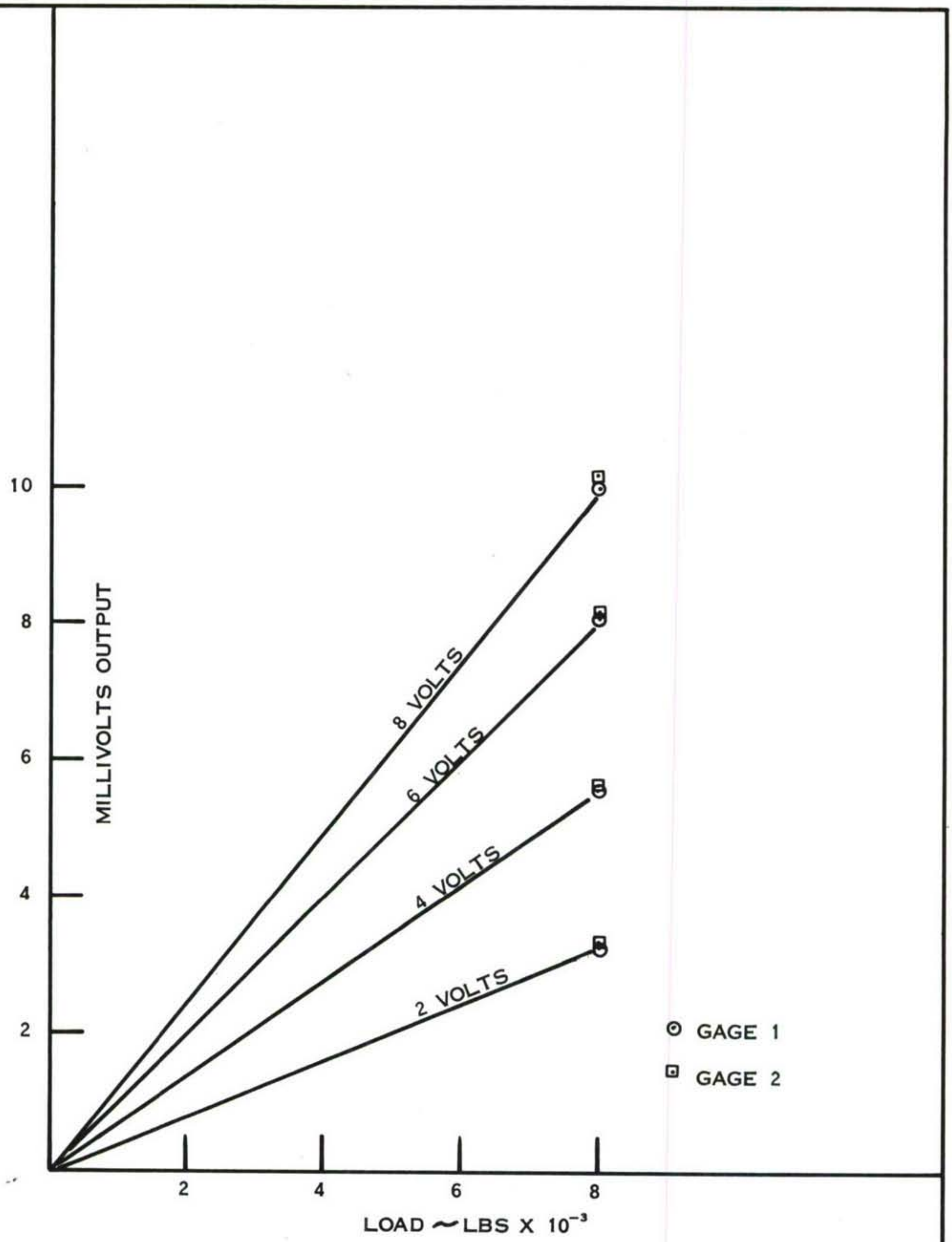


FIGURE 25 EFFECTS OF BRIDGE VOLTAGE ON STRAIN SENSITIVITY OF TWO FULL BRIDGE STRAIN GAGES AT 75°F ON INCONEL X–750, SPECIMEN NO. 2

B. Tests Performed at Elevated Temperatures

1. Quartz Sensitivity

Quartz sensitivity of a Full Bridge strain gage was determined in the following manner:

A Full Bridge strain gage was cemented on a 1" diameter Vycor tube (96% quartz) with B-144 cement. After the gage was fully cured at 600° F., the instrumented quartz tube was placed inside a furnace. When completing the electrical connections the bridge was initially balanced for zero strain and its output applied to a strain indicator at a gage factor setting of 4.00. A Chromel-Alumel thermocouple, part of the gage installation, was used to monitor the temperature. Tests were performed for two repeatable temperature cycles over the range of 75 to 1100° F.

Tabulated results of the tests are shown below and the curve of apparent strain vs. temperature is shown in Figure 26.

Temp.	Strain - Micro Inches per Inch	
° F.	1st Cycle	2nd Cycle - x 10^6
75	--	--
200	615	546
400	1760	1786
600	2925	3096
800	3990	4336
900	--	4941
1000	4880	5536
1050	--	5761
1100	--	5961

Duration of test was approximately 50 minutes.

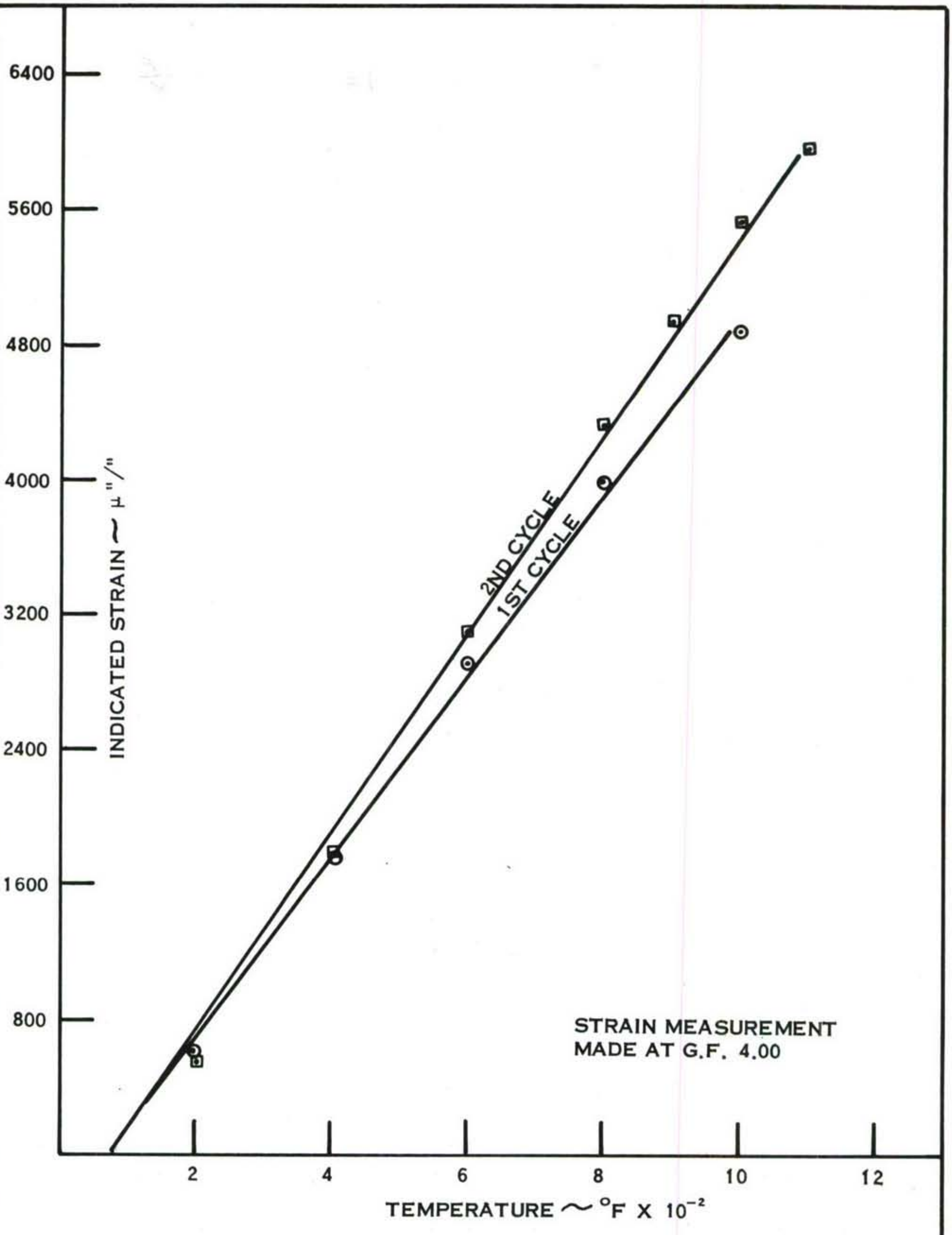


FIGURE 26 APPARENT STRAIN OF A FULL BRIDGE STRAIN GAGE ON QUARTZ

The quartz sensitivity of the gage was determined as follows:

$$e \text{ (ind. strain)} \left(\frac{G.F.}{K_s}\right) = (\alpha_s - \alpha_f)\left(\frac{G.F.}{K_s}\right)\Delta T + b \cdot \Delta T \quad (12)$$

where G.F. - the assumed gage factor setting used in recording strain

K_s - the bridge sensitivity factor of the gage

α_s - the thermal coefficient of expansion of the test specimen to which the gage was bonded

α_f - the thermal expansion of the Full Bridge strain gage

ΔT - the temperature change

b - the thermal coefficient of resistivity of the Full Bridge strain gage.

If the bridge is initially balanced and all the arms have equal change in resistance, then b is zero for the bridge and the total change in strain may then be expressed as

$$e \text{ (ind. strain)} = (\alpha_s - \alpha_f)\,\Delta T \quad (13)$$

For e = 5961 micro-inch per inch

$\alpha_s = .8 \times 10^{-6}$ inches per inch per °F.

ΔT = 1025° F.

$5961 = (.8 - \alpha_f)\ 1025$

$5961 - 820 = -1025\,\alpha_f$

$\frac{5141}{1025} = -\alpha_f$

$5.06 = -\alpha_f$

$5.06 \times 10^{-6} = -\alpha_f$

The minus sign in front of $-\alpha_f$ can be explained in the following manner. As the temperature rises, the strain gage tries to expand longitudinally but is prevented from doing so by the cement bonding it to the quartz base. However, the cross section of the gage is free to expand radially, thereby increasing the cross-sectional area, decreasing the electrical resistance and thus producing a negative component.

2. Photographic Evaluation

A test specimen, designated as test specimen C, was used in the preliminary investigation of recording strain photographically at room and elevated temperatures.

The test specimen, 3/4" diameter x 17", was specially machined to include four ground surfaces, 1/2" x 1/2" cross sectional area by 10" in length. Four holes, approximately 0.040" diameter x 0.050" deep, were drilled in the center of the beam 1/4" apart, on the lateral and vertical axis. A fifth hole was drilled equidistant from the four holes. The drilling was done on a Bridgeport machine within the accuracy of its optical readout, which is ± 0.0001".

Test specimen C was placed directly on the optical comparator and measurements between the axial and lateral markings were then noted under 100 power magnification and recorded. The test specimen was then installed in the tensile test machine and the markings on the specimen were photographed on a glass plate. Measurements of the reproduced markings as indicated on the optical comparator under a 100 power magnification were recorded. The tabulated data is shown in Table 17.

TABLE 17

MARKING DISPLACEMENT MEASUREMENTS AS PERFORMED ON THE OPTICAL COMPARATOR FOR PHOTOGRAPHIC EVALUATION

Number of Readings	Direct	Photographed	Axis
1	.24980	.19905	Vertical
2	.25000	.19895	
3	.25000	.19910	
4	.25010	.19920	
5	.25025	.19920	
6	.25019	.19915	
1	.25019	.19870	Lateral
2	.25020	.19885	
3	.25025	.19890	
4	.24990	.19895	
5	.25000	.19890	
6	.24995	.19880	

The direct and photographed measurements between the axial and lateral markings as indicated in Table 17 is the difference in two readings for statistical measurement for photographic evaluation.

3. Effects of Temperature on a Full Bridge Strain Gage Installed on a Nickel Specimen:

A nickel test specimen with two installed Full Bridge strain gages was placed vertically in the enclosed furnace in an unrestrained position i.e., bottom end fixed and opposite end free to expand. Two thermocouples, placed across the 1/4" gage length, monitored the variation in temperature.

Both strain gages were balanced initially for zero strain output at gage factor setting of 4.00 as indicated on a strain indicator. A temperature cycle from 75° to 920° F. was applied to the specimen and the outputsof both Full Bridge strain gages were monitored at each temperature point after it was stabilized.

The test results are shown in Table 18. The effects of temperature on gages 1 and 2 are shown in Figure 27.

Upon completion, the furnace was oriented for photographing the marking displacement. After rebalancing both Full Bridge strain gages, the dots were photographed and zero strain of both gages recorded. An additional thermal cycle 75° to 1200° F. was applied to the specimen in 400° increments for three repeatable cycles. Upon reaching stabilization at each temperature point, the dot displacement and strain gage output were simultaneously recorded. A typical data sheet used in recording displacement measurements is illustrated in Table 19. Results are shown in Table 20.

Afterwards, the nickel beam was removed from the furnace and reinstalled in the tensile test machine. A 1" optical gage was placed on the beam. A load from 0 to 8000 lbs. in 1000 lb. increments was applied to the specimen at room temperature. The optical gage output as shown in Table 19 was recorded at each load point and strain vs. load plotted, as indicated in Figure 29.

Results indicate a definite change in the nickel structure after its exposure to 1200° F. This change was indicated by both Full Bridge strain gages and the photographic displacement measurements. The change in the nickel material conforms to its physical characteristics, which are as follows:

1. Recrystallization temperature - 1112° F.
2. Annealing temperature - 1200° F.
3. Thermal expansion - 9.36 x 10^6 (75-1200° F.)

It was decided that nickel could not be used as material for elevated temperatures because of its instability above 1200° F.

As a result of numerous investigations, an error was noted in the photographic measurements of small displacements. For an applied load of 10,000 lbs., (approximately 1000 microstrain) the photographic displacement of dots on either Nimonic or nickel specimens for 1/4" gage length was approximately 0.0001 inches. However, the optical comparator is only accurate to 0.0001" as indicated by the least count of its micrometer vernier. Therefore, to decrease the error in the photographic measurement, material of greater elongation was required for further evaluation of the photographic system.

By using aluminum, an equivalent load of 10,000 lbs., on a 1/2" x 1/2" test specimen increased the strain to 4000 micro inches per inch, and by increasing the gage length to 3/4" the load increased the displacement between the dots to 0.0020 inches.

TABLE 18

EFFECTS OF TEMPERATURE SENSITIVITY ON TWO FULL BRIDGE STRAIN GAGES INSTALLED ON A NICKEL TEST SPECIMEN

Specimen Material: Nickel test specimen C

Strain recorded on a strain indicator at gage factor = 4.00.

Strain Measurements - Micro Inch Per Inch

Temp. ° F.	Gage 1C	Corrected for K_s = 6.55	Gage 2C	Corrected for K_s = 7.01
75	-	-	-	-
174	870	530	810	462
199	1085	662	1025	584
270	1765	1077	1660	946
298	2025	1235	1920	1094
358	2535	1546	2430	1385
530	4250	2593	4035	2300
693	5940	3623	5700	3249
786	6740	4111	6510	3711
863	7275	4438	7090	4041
900	7405	4517	7220	4115
920	7435	4535	7225	4118

The markings were not photographed during this test. Temperature sensitivity recorded is the effect of gage installation and specimen's elongation.

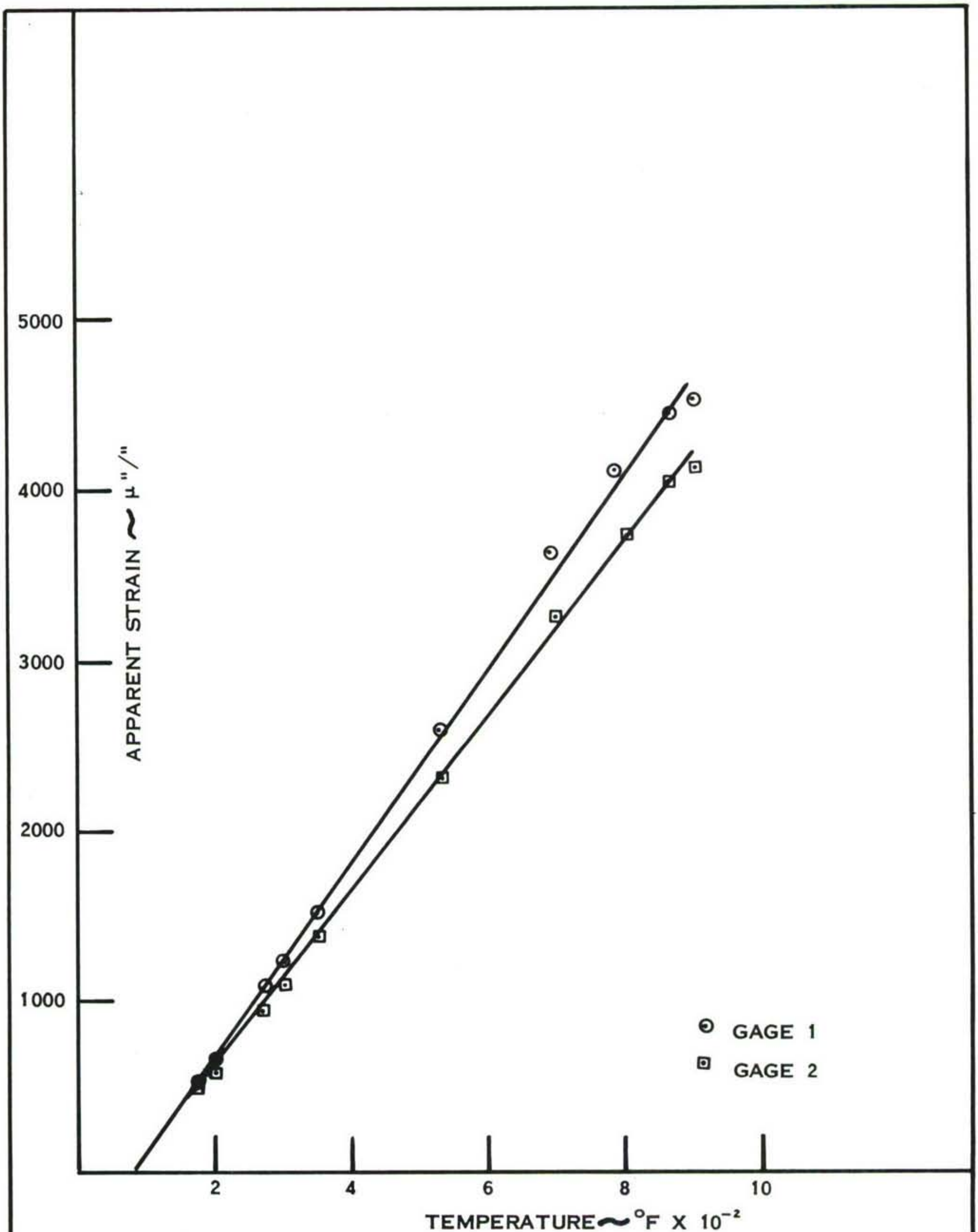


FIGURE 27 EFFECTS OF TEMPERATURE SENSITIVITY OF TWO FULL BRIDGE STRAIN GAGES ON NICKEL

TABLE 19

TYPICAL DATA SHEET USED IN RECORDING DISPLACEMENT MEASUREMENTS ON THE OPTICAL COMPARATOR

Description of Specimen: Nickel Test Specimen 1/4" Gage Length

Date: 8-20-63

Operator:

Remarks:

Test Procedure: Measurement made at 100 power

Vertical Axis

No. of Readings	Initial	Final	Difference	Deviation
1	.37895	.57740	.19845	0.00006
2	.37910	.57765	.19855	0.00016
3	.37920	.57750	.19830	0.00009
4	.37910	.57770	.19860	0.00021
5	.37940	.57760	.19820	0.00019
6	.37935	.57760	.19825	0.00014
7	.37930	.57770	.19840	0.00001
8	.37930	.57760	.19830	0.00009
9	.37920	.57770	.19850	0.00011
Mean =			.198393	
a.d. =				0.00012

$$A.D. = \frac{a.d.}{\sqrt{n}} = \frac{0.00012}{3}$$

Length = 0.19839 ± 0.00004 in.

TABLE 20

A THERMAL EXPANSION MEASUREMENT BY THE PHOTOGRAPHIC STRAIN METHOD ON A NICKEL TEST SPECIMEN

Specimen Material: Nickel test specimen C - 1/4" optical gage length

Temperature Range: 75-1200° F. - for three repeatable cycles

Strain output recorded on a strain indicator at gage factor = 4.00.

Photographic displacement measured in inches on the optical comparator under 100 power magnification in accordance with the typical data sheet shown in Table 19.

Temp. ° F.	Strain Measurement Micro Inch Per In. Gage 1C	Gage 2C	Photographic Displacement-Inches (Avg. of 9 Readings)	Photographic Strain Measurement Micro "/"	Thermal Expansion Coefficient x 10^{-6}
First Cycle					
75	--	-	.19719	--	--
400	3108	2900	--	--	--
438	3193	3259	.19740	1064	--
797	7280	7850	.19839	6085	8.662
1192	9304	8550	.19911	9736	8.649
75	+6310	+5630	.19833	5781	-
Second Cycle					
75	--	--	.19833	--	--
400	5145	4508	.20025	9680	--
801	14388	9983	.20090	12958	--
1199	13728	11380	.20192	18101	17.87
75	+7045	+8705	.2006	11445	16.10
Third Cycle					
75	Gage failed	--	.20021	--	--
800	--	14860	.20170	7442	10.055
1175	--	19710	.20189	8391	7.491
75	--	+940	.20021	--	--

Table 20 (Continued)

1) Photographic strain measurement was determined by the following equation:

$$\frac{L_1 - L_0}{L_1} = \text{strain in micro inches per inch}$$

where L_1 is the final length in inches

L_0 is the original length in inches

2) Thermal coefficient of expansion due to photographic strain measurement was determined as follows:

$$\alpha = \frac{\Delta L}{L_0 \Delta T}$$

where ΔL is the change in length in inches

L_0 is the original length in inches

ΔT is the corresponding change in temperature.

The thermal expansion tabulated data was used for comparison between the theoretical and handbook value.

TABLE 21

EFFECTS OF MECHANICAL LOADING ON THE OPTICAL GAGE

Specimen Material: Nickel test specimen - C

Test performed at room temperature after exposure to 1200° F.

A displacement of 1 division = 400 micro-inch per inch strain.

Load Lbs.	Displacement Divisions		Strain Micro Inch Per Inch
0	17.60	--	--
1000	17.26	.34	136
2000	16.90	.70	280
3000	16.54	1.06	424
4000	16.18	1.42	568
5000	15.78	1.82	728
6000	15.40	2.20	880
7000	14.98	2.62	1048
8000	14.52	3.08	1232
7000	14.84	2.76	1104
6000	15.20	2.40	960
5000	15.56	2.04	816
4000	15.94	1.66	664
3000	16.30	1.30	520
2000	16.74	.86	344
1000	17.14	.46	184
0	17.56	.04	16

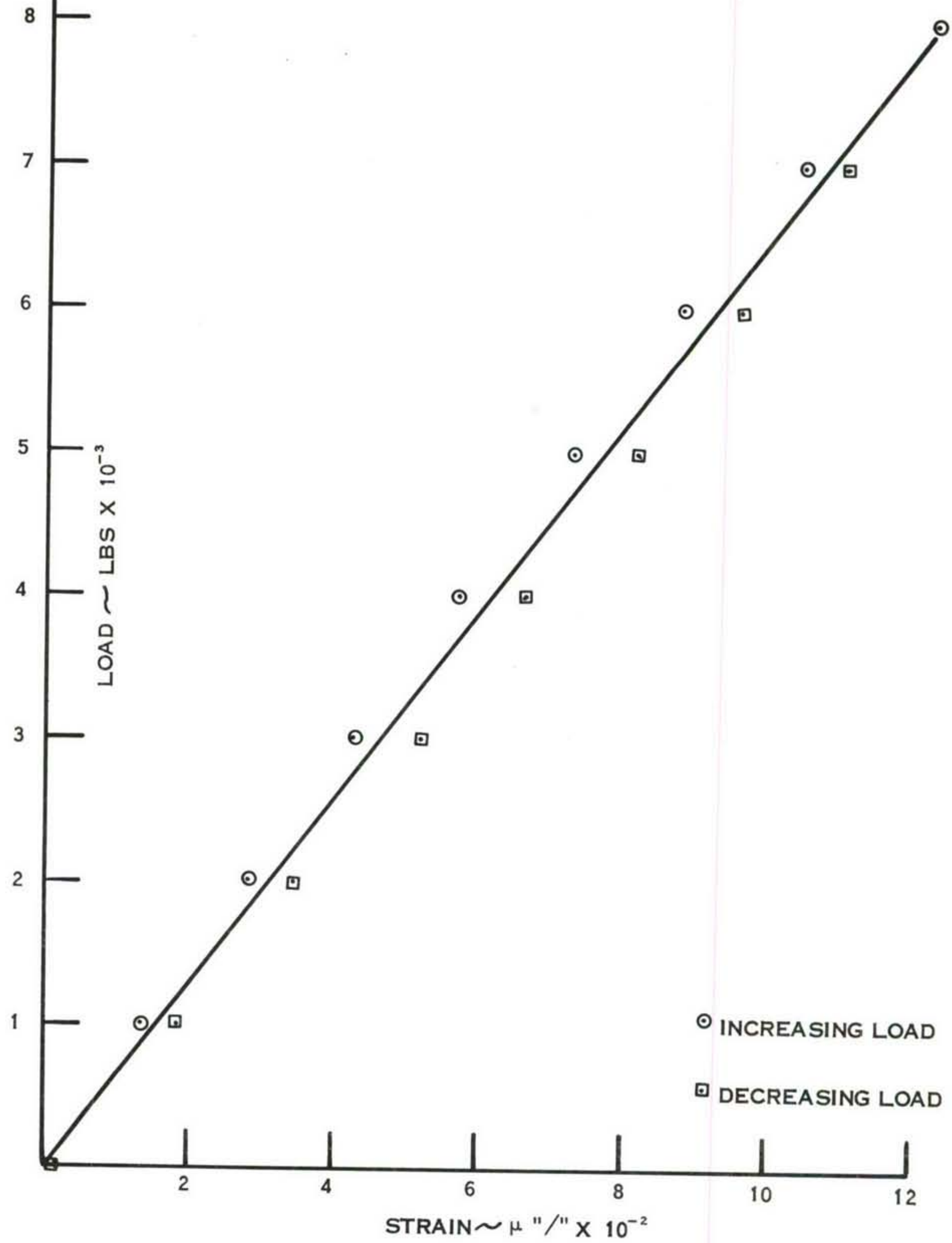


FIGURE 28 STRAIN SENSITIVITY OF AN OPTICAL GAGE AFTER EXPOSURE TO 1200°F AT 75°F ON NICKEL

4. Comparison Between the Photographic Method and the Optical Gage to 600° F.

An aluminum test specimen 1/2" x 1" cross sectional area, with a 3/4" gage length, was initially used for evaluation of the photographic strain method. The markings were photographed at room temperature while subjecting the specimen to an axial load from 0 to 12,000 lbs. Resultant data is indicated below:

Load Lbs.	Calc. Strain μ "/"	Photographic Displacement- Inches	Photographic Strain Measurement μ "/"
0	-	0.5125	-
6000	1143	0.5132	1365
12000	2286	0.5137	2300

Strain was calculated as follows:

$$e_{calc.} = \frac{P}{A\,E_M}$$

where P is the load in lbs.

A is the cross sectional area

E_M is the modulus of elasticity which is equal to 10.5×10^6 psi.

The photographic strain measurements were based on the following equation:

$$\frac{\Delta L}{L_o}$$

where ΔL is the change in length in inches

L_o is the original length in inches

An aluminum bar 1/2" x 1/2" cross sectional area x 30" long with two holes 3/4" apart was used in the following test.

With the specimen installed in the test machine, a 1" optical gage was aligned on the opposite side of the two markings. An axial load of 5000 and 10,000 lbs. was then applied to the specimen. The optical gage displacement was noted and the dot displacement photographed at each load point.

Tabulated data is shown below:

Load Lbs.	Calc. Strain μ "/"	Photographic Displacement (Inches)	Photographic Strain μ "/"	Optical Gage μ "/"
0	--	0.517366	-	-
5000	1905	0.518183	1579	1840
10000	3808	0.51955	4285	3729

With the specimen still installed in the tensile test machine and the attached camera focused on the markings, an axial load from 0 to 7000 lbs. was applied to the specimen in 1000 lb. increments. The optical gage displacement was recorded at each point while the dot displacement was photographed only at zero, 2000 and 4000 lb. load points. The optical gage and the photographic dot displacement were recorded simultaneously.

Test results are shown in Table 22 and the stress-strain comparison curve between the optical gage and the photographic strain method in Figure 29.

Upon completion of the test, the test specimen together with the 1" optical gage were enclosed in a furnace and reinstalled in the test machine. The gage displacement was viewed through the quartz window. The test specimen was then subjected to a mechanical and thermal loading over the temperature range of 75° to 600° F. At reaching stabilization of each temperature point, the gage output was recorded over a predetermined mechanical load. Temperatures were observed and recorded at each end of the specimen (adjacent to the heated area) and at the gage length extremities. Test results are indicated in Table 23 and stress-strain curves for various temperatures in Figure 30. Resultant modulus change between the experimental values and the theoretical values found in Military Handbook -5 is illustrated in Figure 31.

The maximum loads applied to the test specimen were derived from calculations based on the Military Handbook values. Type material used was aluminum 2024-T3 with the following physical characteristics:

Modulus change - 24% at 600° F.
Ultimate tensile strength - 64,000 PSI
Ultimate tensile strength - 15,000 PSI at 600° F.
Yield strength - 42,000 PSI
Thermal expansion coefficient - 12.6 x 10^{-6} (75-212° F.)

The following test was performed on a 1" optical gage which was installed on the specimen over the temperature range of 75° to 600° F. A 500 lb. preload was maintained on the specimen while the temperature on the specimen was increased. The recorded gage displacement was tabulated as follows:

Temp. ° F.	Optical Gage Displacement	Optical Gage Strain Micro "/"
75	-	-
200	2.22	888
353	5.72	2288
524	11.56	4624
537	12.34	4936
576	12.84	5136
585	12.90	5160

At the completion of the test, the 1" optical gage was removed and the furnace oriented towards the camera for photographing the dots. An additional thermal and mechanical load cycle was applied to the specimen from 75° to 600° F. At each stabilized temperature point, the dots were photographed and their displacement measured on the optical comparator. Test results are recorded in Table 24 and a plot of the modulus change in Figure 31.

The test results indicate a decrease in percentage error between the optical gage and the photographic method as the load is increased. Table 22 shows a deviation of 23% between the optical gage and the photographic strain method at 2000 lbs., and 16% deviation at 4000 lbs.

Results show improvement in the photographic strain method with repeatable temperature cycles.

TABLE 22

COMPARISON BETWEEN THE OPTICAL GAGE AND THE PHOTOGRAPHIC STRAIN METHOD AT ROOM TEMPERATURE

Test Specimen: Aluminum 2024-T3 material (1/2" x 1/2")

A displacement of 1 division = 400 micro-inch per inch

Load Lbs.	Optical Gage Displacement	Optical Gage Change	Optical Gage Strain μ"/"	Photographic Strain Method Displacement	Photographic Strain Method Corresponding Strain μ"/"
0	9.20	-	-	0.51735"	-
1000	10.12	.92	368	-	-
2000	11.02	1.80	720	0.51785	889
3000	11.94	2.74	1096	-	-
4000	12.84	3.64	1456	0.51830	1704
5000	13.80	4.60	1840	-	-
6000	14.74	5.54	2216	-	-
7000	15.66	6.46	2584	-	-
8000	16.64	7.44	2976	-	-
7000	15.72	6.52	2608	-	-
6000	14.80	5.60	2240	-	-
5000	13.84	4.64	1856	-	-
4000	12.90	3.70	1480	-	-
3000	11.96	2.76	1104	-	-
2000	11.06	1.86	744	-	-
1000	10.12	.92	368	-	-
0	9.20	-	-	-	-

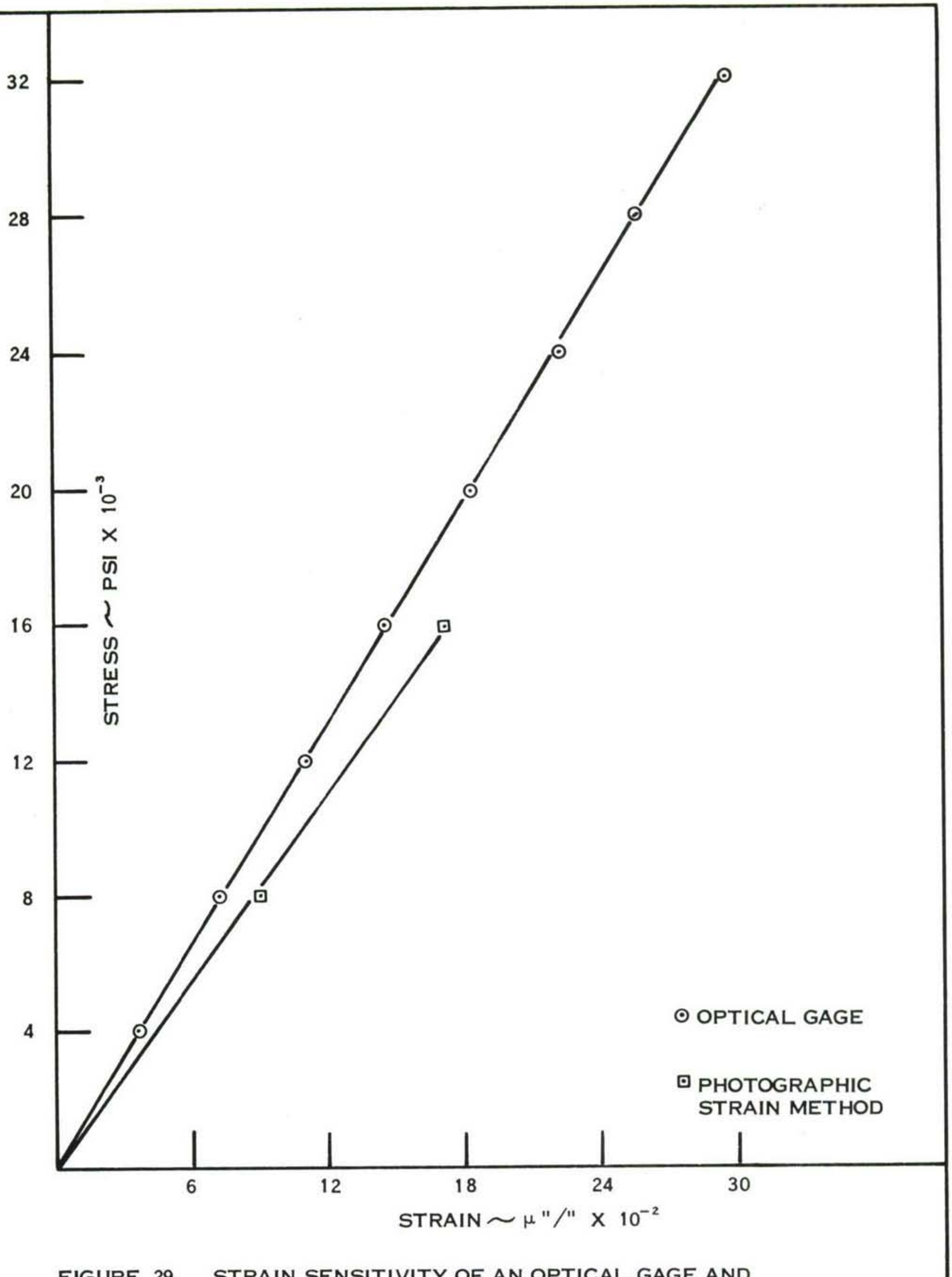


FIGURE 29 STRAIN SENSITIVITY OF AN OPTICAL GAGE AND PHOTOGRAPHIC STRAIN METHOD AT 75°F ON ALUMINUM

TABLE 23

EFFECTS OF MECHANICAL LOADING ON THE OPTICAL GAGE AT ELEVATED TEMPERATURES

Date of Test: 9-16-63

Test Specimen: Aluminum 2024-T3 material (1/2" x 1/2" x 30")

A 1" optical gage was viewed through the quartz window.

A displacement of 1 division = 400 micro-inch per inch.

		Optical Gage		
Temp. ° F.	Load Lbs.	Displacement	Change	Strain - Micro "/"
75	0	4.64 div.	-	-
	2000	6.48	1.84	736
	4000	8.36	3.72	1488
	6000	10.24	5.60	2240
200	0	6.82	-	-
	2000	8.74	1.92	768
	4000	10.70	3.88	1552
	6000	12.64	5.82	2328
343-353	0	10.34	-	-
	2000	12.40	2.06	824
	4000	14.44	4.10	1640
	6000	16.52	6.18	2472
537-550	0	16.60	-	-
	1000	17.74	1.14	456
	2000	18.86	2.26	904
	3000	20.10	3.50	1400
585	0	17.60	-	-
	500	18.20	0.60	240
	1000	18.80	1.20	480
	1500	19.40	1.80	720
	2000	20.00	2.40	960

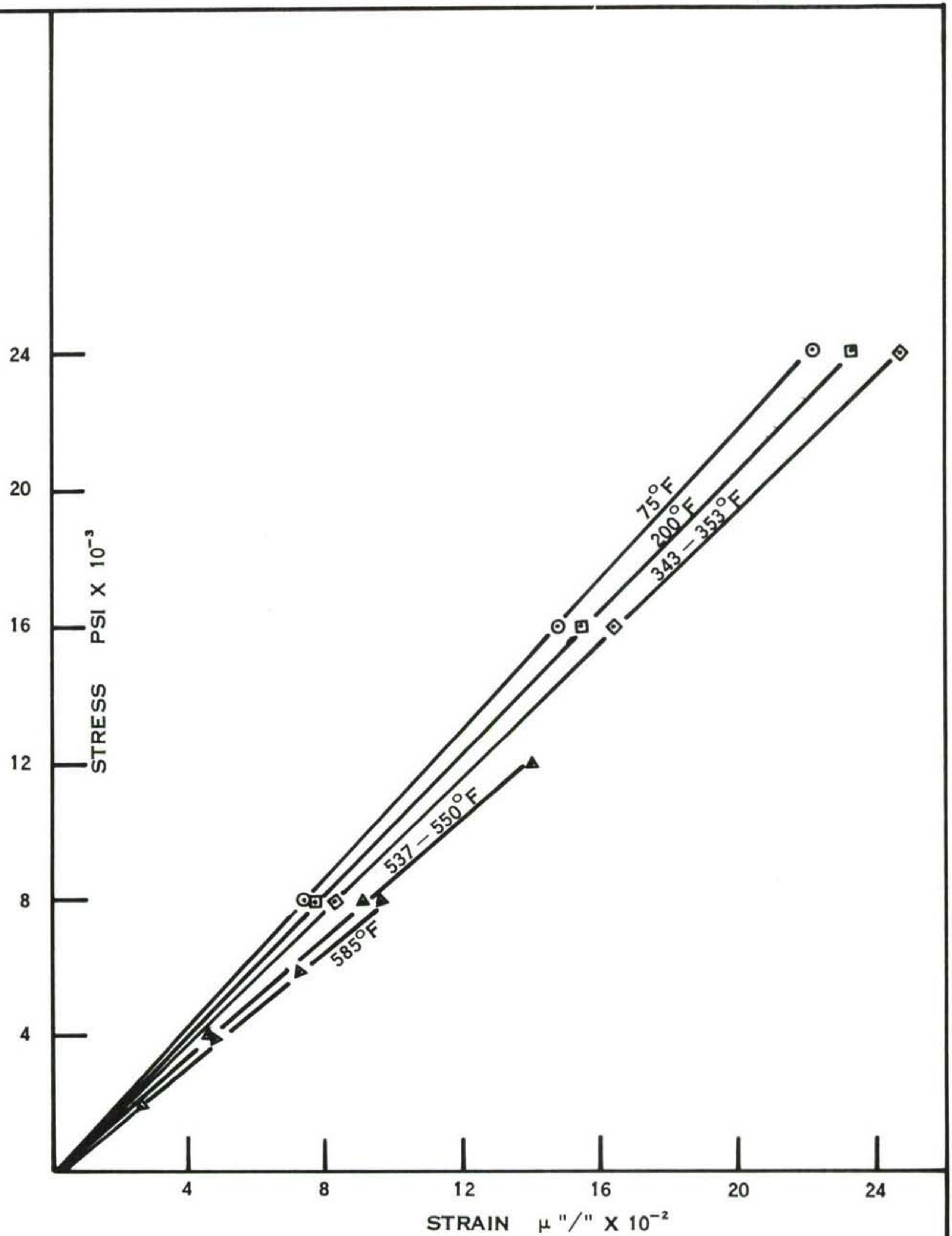


FIGURE 30 EFFECTS OF TEMPERATURE ON STRAIN SENSITIVITY OF AN OPTICAL GAGE ON ALUMINUM

TABLE 24

EFFECTS OF THERMAL AND MECHANICAL LOADING ON THE OPTICAL GAGE AND THE PHOTOGRAPHIC STRAIN METHOD

Specimen: Aluminum 2024-T3 - 3/4" gage length

Photographic displacement: based on the average of nine readings.

Multiple exposure shots were photographed during the mechanical loading and only single exposures were used for measuring the displacement due to variation in temperature.

Measurements recorded on a 1" optical gage and converted directly into strain.

Temp. ° F.	Maximum Load	Strain μ"/"	Modulus x 10^6 psi
1st Cycle - Optical Gage			
75	6000 lbs.	2240	10.70
200	6000 lbs.	2328	10.39
537-550	3000 lbs.	1400	8.57

2nd Cycle - Photographic Method

	Displacement		Photographic			Calc.	Max.	Theoretical
Temp. ° F.	Zero Load Inches	Max. Load Inches	Change Inches	Strain μ"/"	Stress Psi	Stress Modulus Psi	Load lbs.	Modulus x10^6 psi
75	.52395	.52535	.0014	2676	28098	32000	8000	10.46
555	.5474	.54815	.00075	1370	10275	14080	3520	7.50
3rd Cycle								
75	.54430	.54590	.0016	2939	30859	32000	8000	10.5
200	.54520	.54690	.0017	3118	32386	32000	8000	10.4
343	.5471	.54815	.00105	1919	18806	24000	6000	9.7
524	.5480	.5492	.00120	2190	17958	16000	4000	8.2

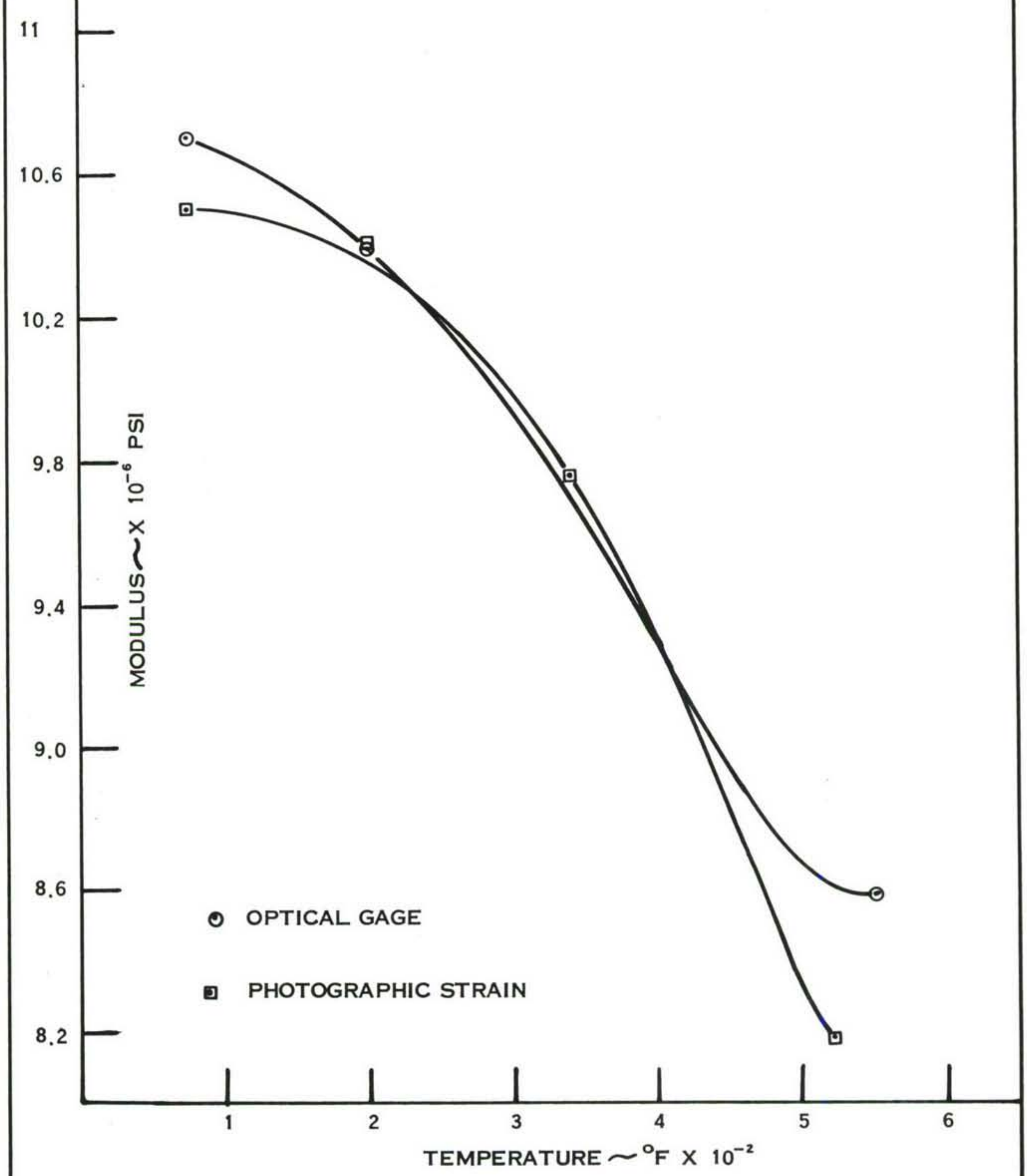


FIGURE 31 EFFECTS OF TEMPERATURE ON MODULUS OF AN OPTICAL GAGE AND THE PHOTOGRAPHIC STRAIN METHOD ON ALUMINUM

C. Test Performance at Elevated Temperatures of a Full Bridge Strain Gage Installed on Inconel X-750 Test Specimen

This section includes the final evaluation of a Full Bridge strain gage at elevated temperatures. The room temperature tests performed on a Full Bridge strain gage installed on two Inconel X-750 test specimens were described in section V, page 59. The same gages and the same test specimens were used for the elevated temperature tests described in this section.

Prior to the performance of the elevated temperature test, the existing furnace described in section V was modified first to include two aluminum oxide coils 1-3/8" o.d. x 4". To prevent any radiation losses the coil heaters were enclosed within a 3-1/2" diameter Alumina tubing. The coil heaters were wound with a 3 mil platinum wire.

Temperature distribution tests were performed first on a Nimonic test specimen installed in the tensile test machine. The instrumented specimen consisted of six thermocouples in locations indicated below:

T/c No. 1 was placed in the center of the specimen
T/c No. 2 - .4" above the center line
T/c No. 3 - .75" above the center line
T/c No. 4 - .3" below the center line
T/c No. 5 - 3.0" below the center line
T/c No. 6 - .3" above the center line.

Thermocouples 1 to 4 covered the gage length area and thermocouples 5 and 6 were located in the hot zone, mid-center of the heater coil.

The temperature distribution curve shown in Figure 32 indicated excessive temperature rise in zones 5 and 6.

The second attempt included the use of Nichrome V wire, 16 ga., (0.051" diameter) in place of the 30 mil platinum wire. The location of the thermocouples was as follows:

T/c 1 at top coil
T/c 2, 3 and 4 were placed over the gage length area
T/c 5 near the bottom coil
T/c 6 - on the back face directly opposite T/c 3.

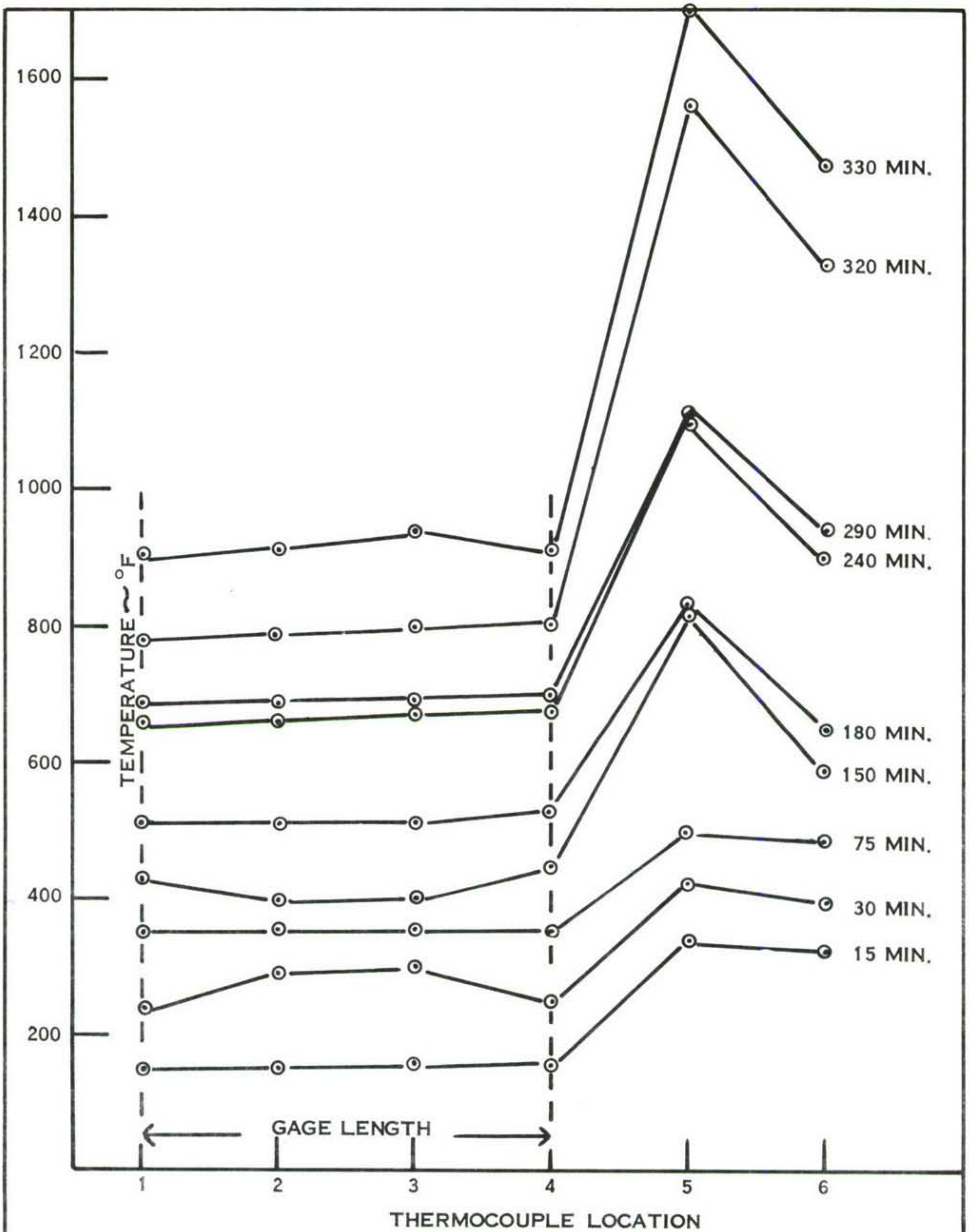


FIGURE 32 EFFECTS OF TEMPERATURE OVER THE GAGE LENGTH DUE TO 30 MIL PLATINUM WIRE FURNACE HEATER ON A NIMONIC TEST SPECIMEN

Results shown in Figure 33 indicate better temperature distribution. Maximum temperature reached in the gage length area was approximately 1500° F., and the temperature recorded on T/c 1 near the top coil was 1750° F. The center lava pieces were removed during this test.

As a result of the previous investigation, the same furnace was then modified to include two separate Nichrome V wound heaters 2" o.d. x 1-1/4" i.d. x 4" long. A 3-1/2" aluminum oxide tube was placed over each heater. The surrounding area between each heater and the alumina tube was filled with granulated fire brick insulation material. The rating of each heater based on the diameter of the coil wire was 600 watts. The furnace was divided into two equal parts for easy installation of the specimen which was placed through the center of the two heaters almost in direct contact with the coils.

Inconel X-750 material was selected for the final evaluation of the Full Bridge strain gage because of its high tensile strength at elevated temperatures. Load vs. temperature curves based on 60% yield were plotted for two cross-sectional areas, see Figure 34. Modulus vs. temperature change is shown in Figure 35. Tensile and yield strength vs. variation in temperature is plotted in Figure 36.

The above information was referenced to values found in "Materials in Design Engineering" handbook.

The following test procedure was utilized to determine the temperature effects on strain sensitivity of a Full Bridge strain gage installed on an Inconel X-750 test specimen.

Two Inconel X-750 test specimens were fabricated, per sketch outlined in Figure 37. Five holes, approximately 0.030" diameter, were centrally located on each test specimen, 0.75" apart in the axial direction and 0.30" apart in the lateral axis. Two Full Bridge strain gages were installed on each specimen on opposite sides of the test specimen, adjacent and 90° away from the markings.

The room temperature test performed on the four Full Bridge strain gages installed on the Inconel X-750 specimens was explained on page 59, section V. Thus the test specimen identified as specimen No. 2, instrumented with two Full Bridge strain gages which were previously tested at room temperature, and six thermocouples, was placed in the modified furnace.

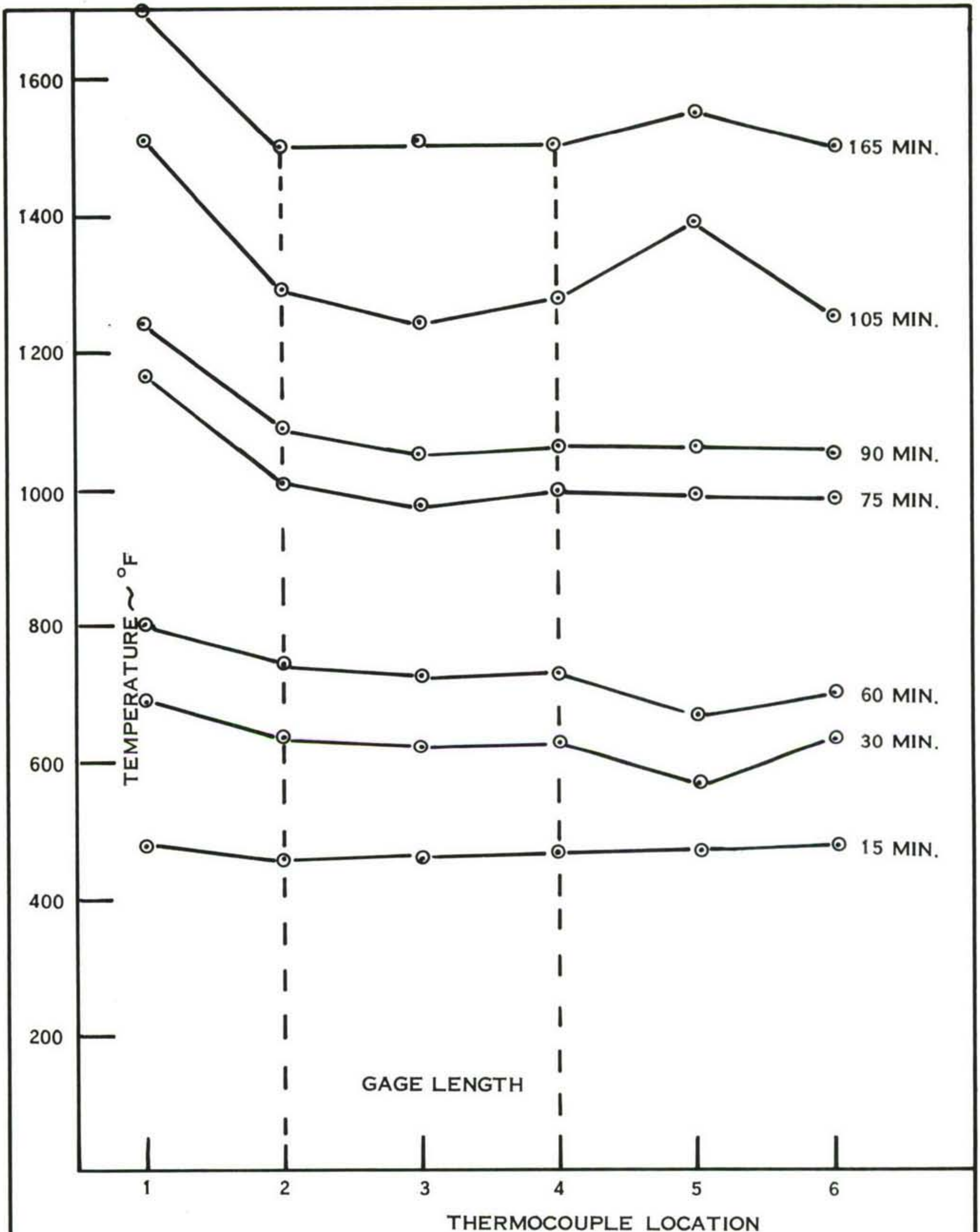


FIGURE 33 EFFECTS OF TEMPERATURE OVER THE GAGE LENGTH DUE TO 16 GAGE NICHROME V WIRE FURNACE HEATER ON A NIMONIC TEST SPECIMEN

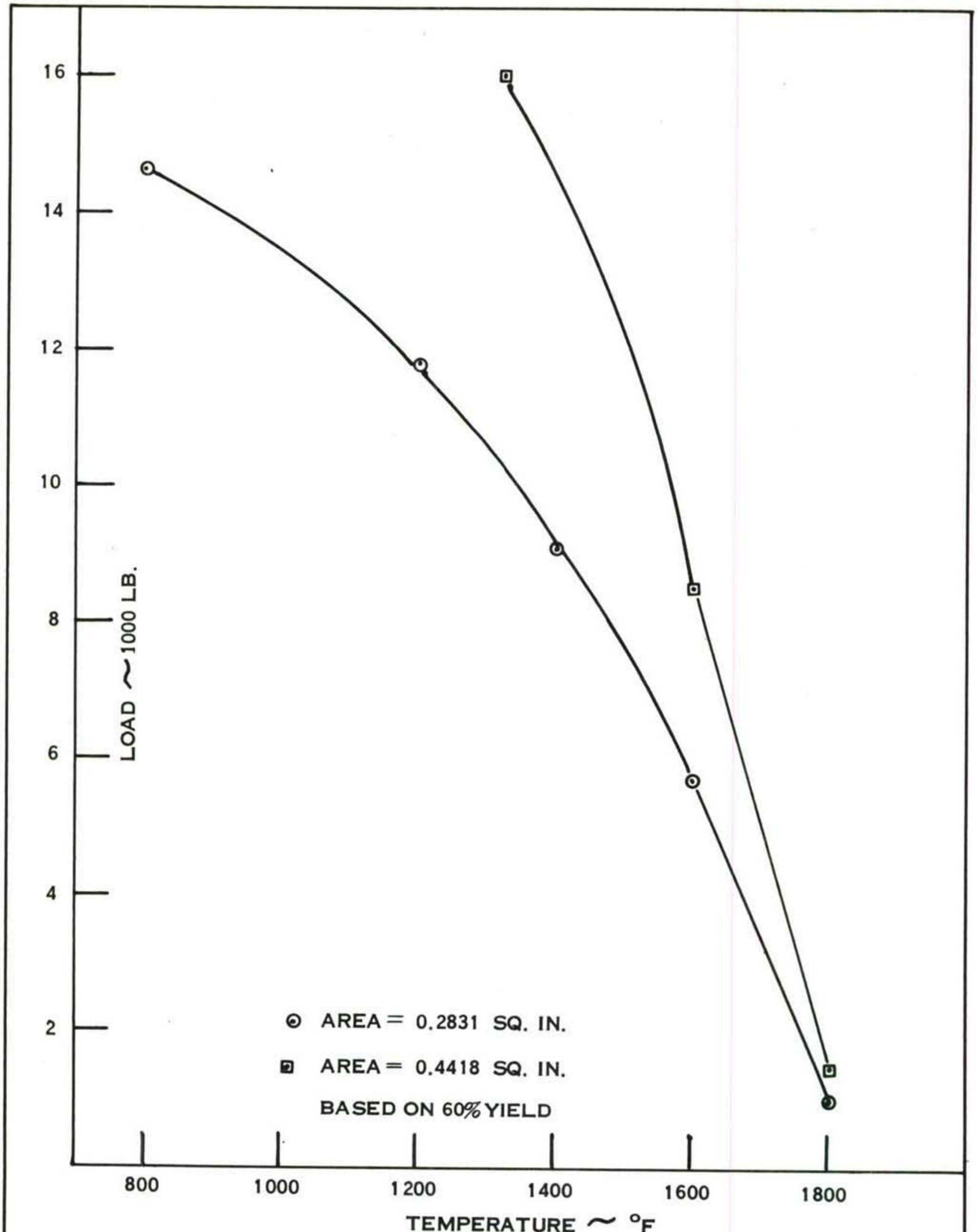


FIGURE 34 EFFECTS OF TEMPERATURE ON LOAD FOR CROSS SECTIONAL AREAS 0.2831 AND 0.4418 SQ. IN. ON INCONEL X–750

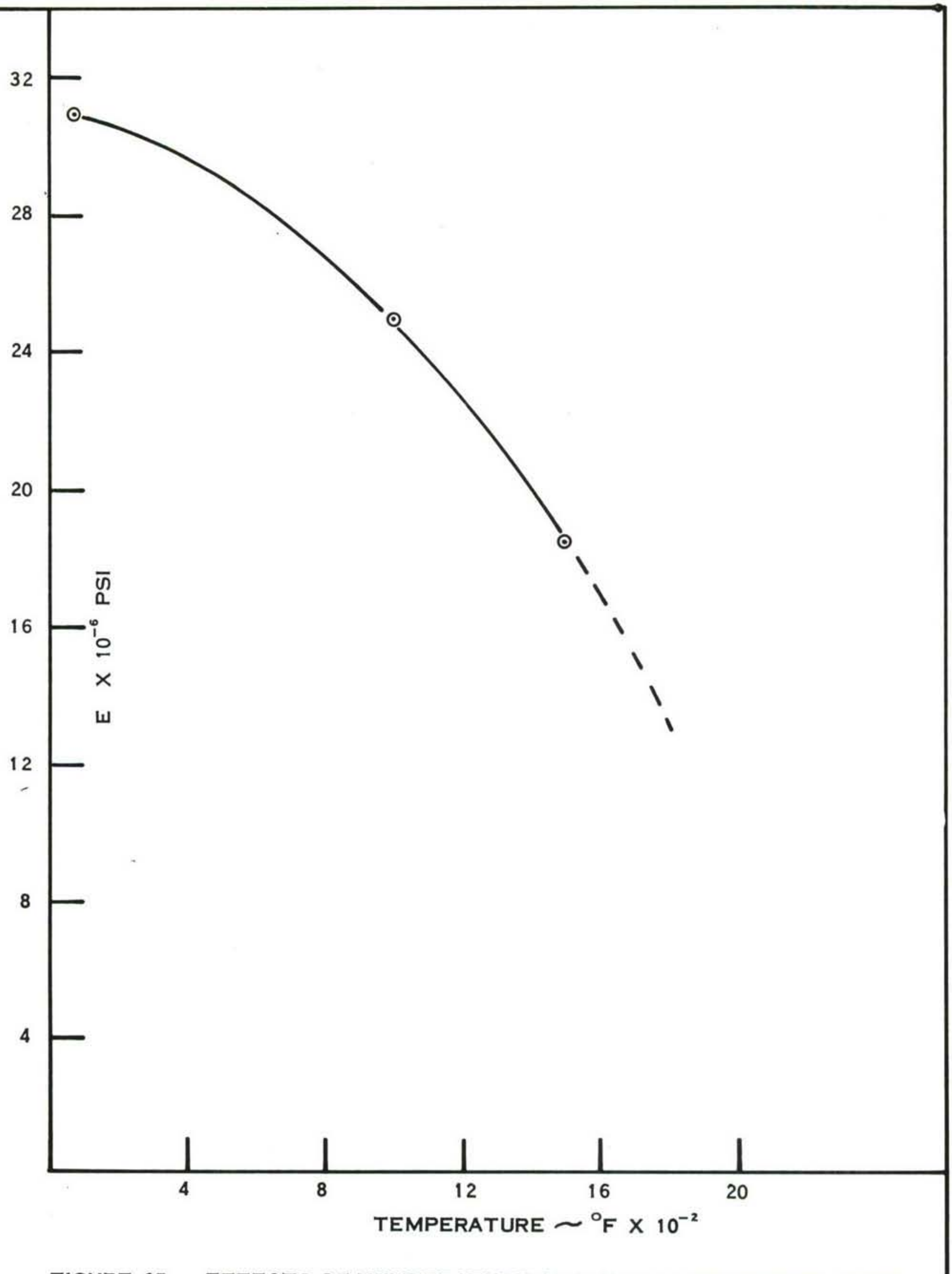


FIGURE 35 EFFECTS OF TEMPERATURE ON MODULUS ON INCONEL X–750

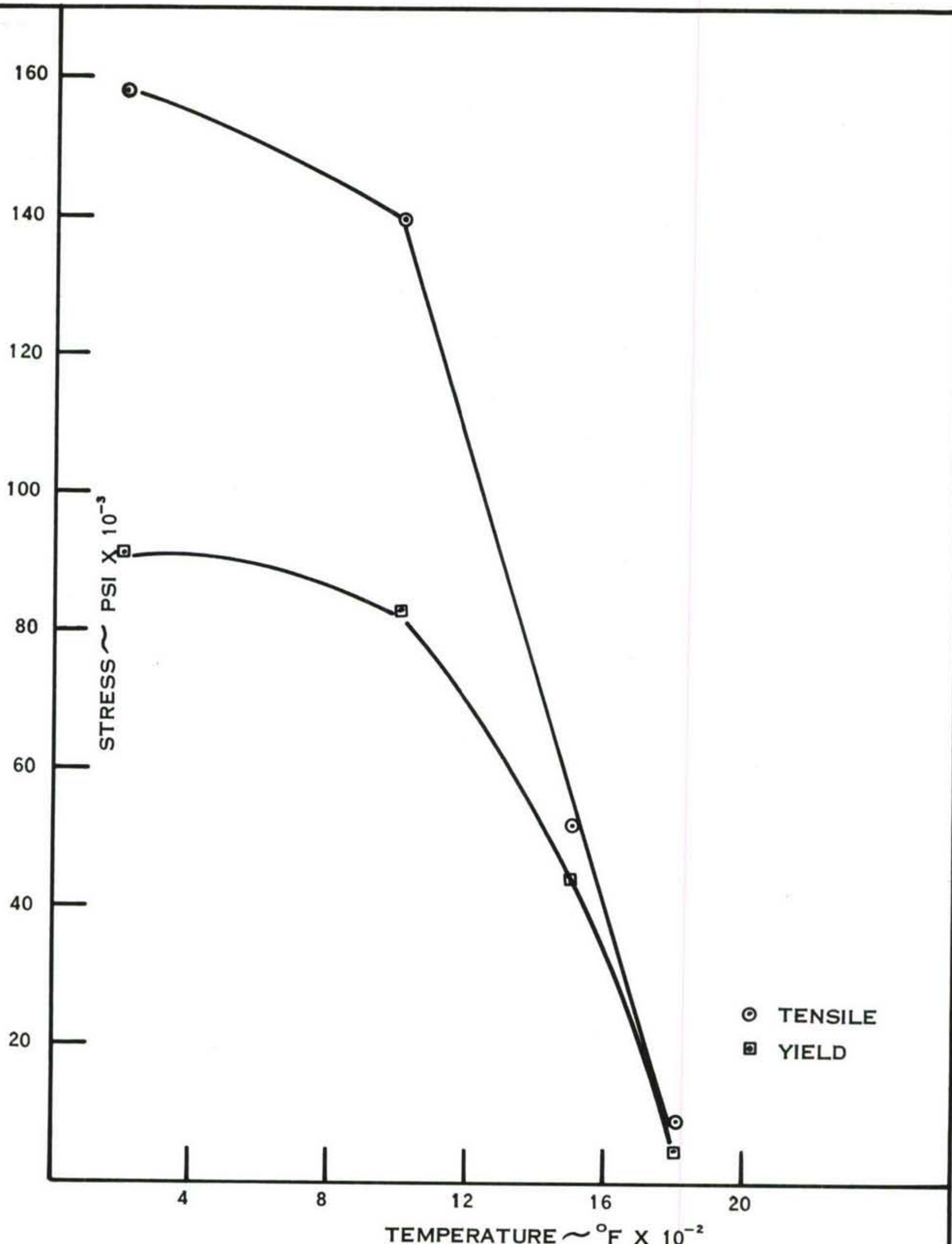


FIGURE 36 EFFECTS OF TEMPERATURE ON TENSILE AND YIELD STRENGTH ON INCONEL X–750

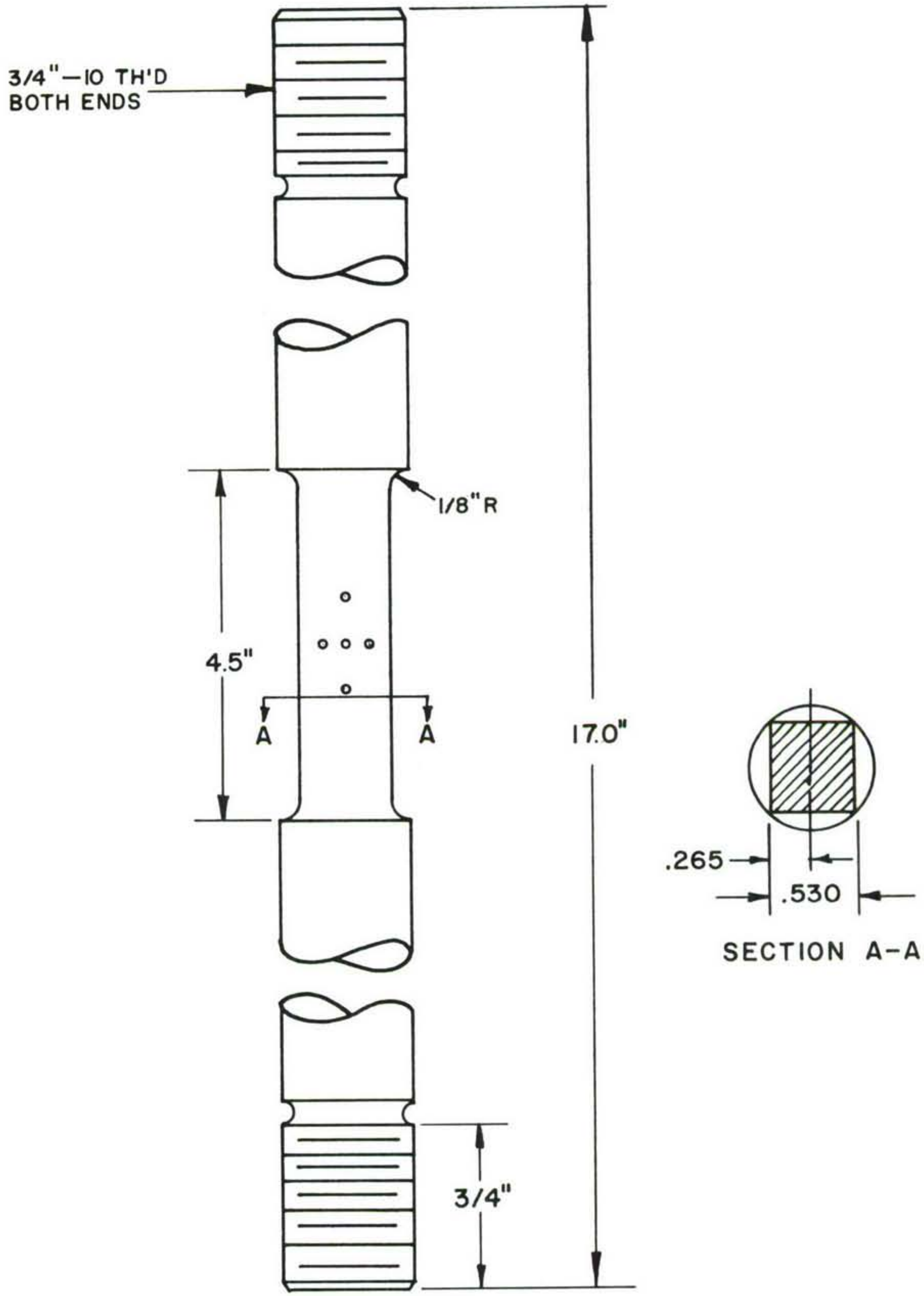


FIGURE 37—MACHINED INCONEL X-750
TEST SPECIMEN

The enclosed specimen was then installed in the tensile test machine. The approximate locations of the six thermocouples are shown in Figure 38. The cross-sectional area of the specimen was measured at 0.2831 square inches.

Afterwards, the specimen was subjected to an axial load from 0 to 9000 lbs., in 3000 lb. increments at room temperature. The gage with 4 volts D.C. applied to the bridge was balanced initially and its output recorded on the Y-axis of the X-Y recorder for each 3000 lb. increment. No signal was applied to the X-axis. Each increment was manually indicated by repositioning the zero control on the X-axis.

A Hasselblad model 500C Reflex camera equipped with an 80 mm lens was used simultaneously in recording the dot displacement both at room and elevated temperatures.

The following procedure was used in the photographic strain measurement. While at zero load both the gage output and the dots were recorded. The specimen was subjected to an axial load from 0 to 9000 lbs., in 3000 lb. intervals at which time only the gage output was monitored. The load was then increased from 9000 to 16,500 lbs., and the dots photographed at the maximum load. After the load was returned to zero the gage was rebalanced and the camera reloaded.

The temperature of the specimen was increased to approximately 500° F. The gage output was recorded and the bridge rebalanced prior to the mechanical loading of the specimen. An axial load from 0 to 9000 lbs. was again applied to the specimen with the output of the gage recorded in 3000 lb. increments. The dots were photographed while at zero load and again at 16,500 lbs.

Upon its return to zero load, the camera was reloaded and the dots once again photographed for the thermal expansion measurement. The temperature was then increased to approximately 850° F., during which time the dots were photographed again using the same glass plate. The thermal expansion of the test specimen was determined by recording the difference in the displacement of the dots at the two subsequent temperature points. The camera was reloaded once again and the bridge rebalanced prior to the mechanical loading of the specimen. The strain gage output was recorded from 0 to 9000 lbs., in 3000 lb. increments and the dots were photographed while at zero load and again at the maximum load of 15,000 lbs.

Upon its return to zero load, the camera was again reloaded and the dots photographed on the unexposed glass slide while still at this temperature. The temperature was then increased to approximately 1400° F., and the dot displacement photographed at a zero load. The camera was again reloaded. An attempt was made to subject the specimen to an axial load from 0 to 2500 lbs. However, the specimen failed due to the temperature gradient existing at the upper end of the test area (2" from the center).

A Platinum-Platinum 13% Rhodium thermocouple was used to measure the specimen's temperature. A Chromel-Alumel thermocouple, part of a gage installation, was used to monitor the gage temperature.

An R cal equivalent was recorded at room temperature prior to the test at elevated temperatures by shunting 30,000 ohms across each of the active arms and noting the millivolt deflection recorded on the Y-axis of the X-Y recorder.

Results of the elevated temperature test completed on gage 1, installed on Inconel X-750 specimen No. 2, are indicated below. The maximum temperature reached was 1400° F. Higher temperatures were not possible because of the existing temperature gradient over the four inch center length of the test specimen as a result of a poor furnace design.

The thermocouple location on the test specimen and the temperature distribution throughout the entire test is expressed below:

Elapsed Time - Minutes	T/c 1 Gage 1	T/c 2 Gage 2	T/c 3 (Upper End) (2" from Center)	T/c 4 Center
90	530° F.	530° F.	540° F.	500° F.
180	913°	913°	1050°	860°
300	970°	970°	1125°	888°
330	905°	906°	1017°	848°
350	1400°	1400°	-	1347°
380	-	-	1992°	1640°

Stress-strain values determined for a cross-sectional area 0.2831 sq. in. (Inconel X-750 - test specimen No. 2) are shown on page 107.

The handbook modulus change vs. temperature is as follows:

31.00×10^6 psi -	75° F.
26.70	866°
23.80	1100°
20.00	1400°

Load Lbs. P	Stress Psi $\sigma = P/A$	Strain μ"/" $(e = \frac{\sigma}{E_M})$ 75° F.	866° F.	1100° F.
150	529	17	20	22
2000	7064	228	-	297
3000	10569	342	397	-
4000	14129	456	-	594
6000	21193	684	794	-
7150	25256	815	-	1061
8000	28258	912	-	-
9000	31790	1025	1190	-
10000	35323	1139	-	-
11150	39385	1270	1475	-
12000	42387	1367	-	-

The resultant millivolt output with 4 volts D.C. applied to the bridge was recorded over the axial load of 0 to 9000 lbs., in 300 lb. intervals at 75° F., 530° F., and 970° F. The tabulated data is shown below:

75° F.

Load Lbs.	Theoretical Strain μ"/"	Output mv.	K_s
0	0	0	0
3000	342	2.15	6.28
6000	684	4.24	6.19
9000	1025	6.30	6.15

R-cal. @ 30K 2.10/2.28 mv.

530° F.

Load Lbs.	Theoret. Strain μ"/"	Output mv.	K_s
0	0	0	0
3000	362	2.32	6.40
6000	724	4.58	6.32
9000	1086	6.70	6.16

R-cal. @ 30K 2.10/2.18 mv.

970° F.

Load Lbs.	Theoretical Strain	Output	K_s
0	0	0	0
3000	407 μ"/"	2.30 mv	5.655
6000	814	4.40	5.40
9000	1221	6.30	5.17

R-cal @ 30K 2.32/2.50 mv.

Bridge sensitivity factor K_s based on the following equation

$K_s = \frac{4 \Delta E_g}{E_i e}$ was derived as follows:

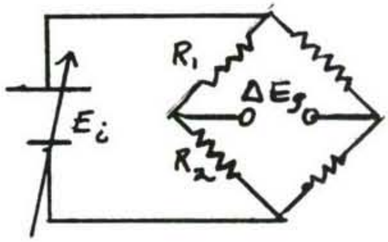
where ΔE_g is the change in millivolt output

$R_1 = R_2 =$ is the gage resistance in ohms in the adjacent legs of a Wheatstone bridge configuration as shown below

E_i is the bridge input voltage in volts D.C.

K_s is the bridge sensitivity factor

e is the strain in./in.



If the resistance change is identical in all legs of the bridge, the factor

$$\frac{R_1 R_2}{(R_1 + R_2)^2} = 0.25 \text{ (constant)}$$

then $$\Delta E_g = \frac{E_i K_s e}{4}$$

$$K_s = \frac{4 \Delta E_g}{E_i e}$$

Hence, based on a 6000 lb. load, K_s at room temperature and 970° F., is 6.19 and 5.40 respectively. This was a decrease of 15% in bridge sensitivity factor, which corresponded to an equivalent modulus decrease. Therefore, the effects of temperature on strain sensitivity at approximately 1000° F. were equal to the modulus change with temperature on a percentage basis.

The photographic strain measurements were recorded in the following sequence:

Set Temp. ° F.	Yield Strength Psi	Safe Load Lbs.	Stress Psi	Strain μ "/"	Modulus E_m $\times 10^6$ Psi	Remarks
75	92,000	16,500	58280	1880	31	Load 0/16500 (Photo No. 1)
530	88,000	16,500	58280	2030	28.7	Load 0/16500 @ 530° F. (No. 2)
530/ 900	-	-	-	-	-	530° to 848 ° F. for thermal expansion measurement (No. 3)
900	85,000	15,150	53500	2060	26	Load 0/15000 (No. 4)
1350	56,000	2,000	35330	1715	20.6	Thermal Expansion 848° to 1340° F. (No. 5)
1400	54,000	-	-	-	19.9	Final load 0 to 2000 lbs. (No. 6)

The above data was based on a 60% yield on an Inconel X-750 material for a cross sectional area of 0.2831 sq. in.

Results of the photographic strain displacement test:

Frame No.	Actual Temp. ° F.	Zero Load	Maximum Load	Change in Inches	Maximum Load Lbs.	Photo. Strain μ "/"	Coefficient of Thermal Expansion
1	75	.5330	.5341	.0011	16,500	2063	-
2	530	.5337	.5351	.0041	16,500	2620	-
3	530/848	marking displacement not clearly photographed.					
4	888	.5359	.5369	.0010	15,000	1865	
5	848/1340	.5346	.5365	.0019	-	-	7.11×10^{-6}
6	1347	specimen failed.					

The photographic strain was determined as follows:

$$\frac{L_1 - L_0}{L_0}$$

where L_1 was the final length
L_0 was the initial length

and the thermal coefficient of expansion was determined by the following method:

$$\alpha = \frac{\Delta L}{L_0 \Delta T} = \frac{L_1 - L_0}{L_0 \Delta T}$$

where L_1 was the final length in inches
L_0 was the initial length in inches
ΔT was the change in temperature.

The specimen failed in an attempt to reach 1500° F. across the cross sectional area. The point of failure occurred at the upper end of the cross sectional area two inches from the center of the specimen. A temperature of 1992° F. was recorded at that point at the time of failure.

Figure 39 illustrates a double exposure displacement of dots over the temperature range of 848° to 1340° F. The clear indication was made at 848° F., however, the exposure at 1340° F. obscures the markings, thus making it difficult to obtain a true measurement of the displacement. The gage installations can be noticed on either side of the test specimen.

Figure 40 was recorded just prior to the failure and Figure 41 indicates the condition immediately after the specimen has failed. The quartz heaters, which were used to deliver additional power, are still on.

On completion of the test, the failed specimen was removed from the tensile test machine. Since gage No. 1 was still operable, the effects of temperature on the resistance were determined. The portion of the specimen with the installed gage was placed in the furnace and the gage's resistance change for a variation in temperature was noted over the temperature range of 75° to 1700° F. The recorded data is shown in Table 25. Resultant data indicates an identical change in resistance in all the legs of the bridge. A 17% change in resistance was recorded upon its return to room temperature.

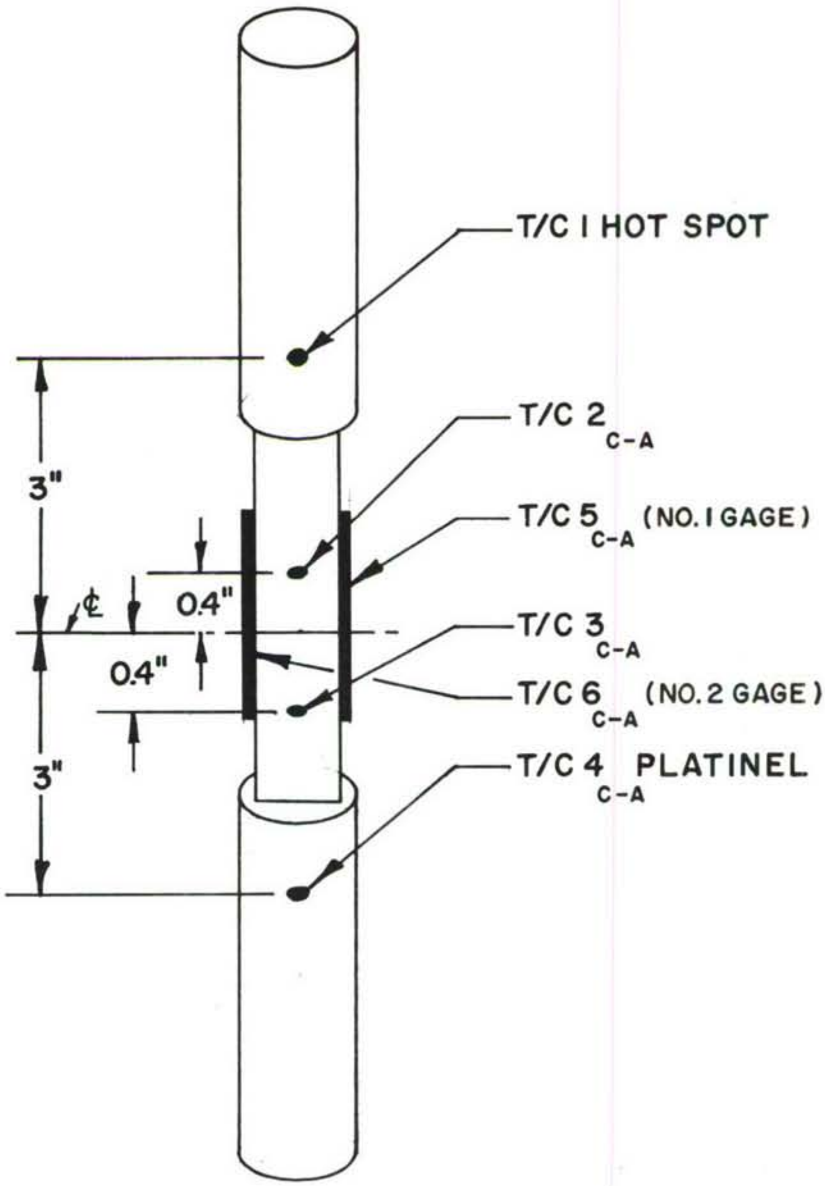


FIGURE 38 – THERMOCOUPLE INSTALLATION ON INCONEL X-750

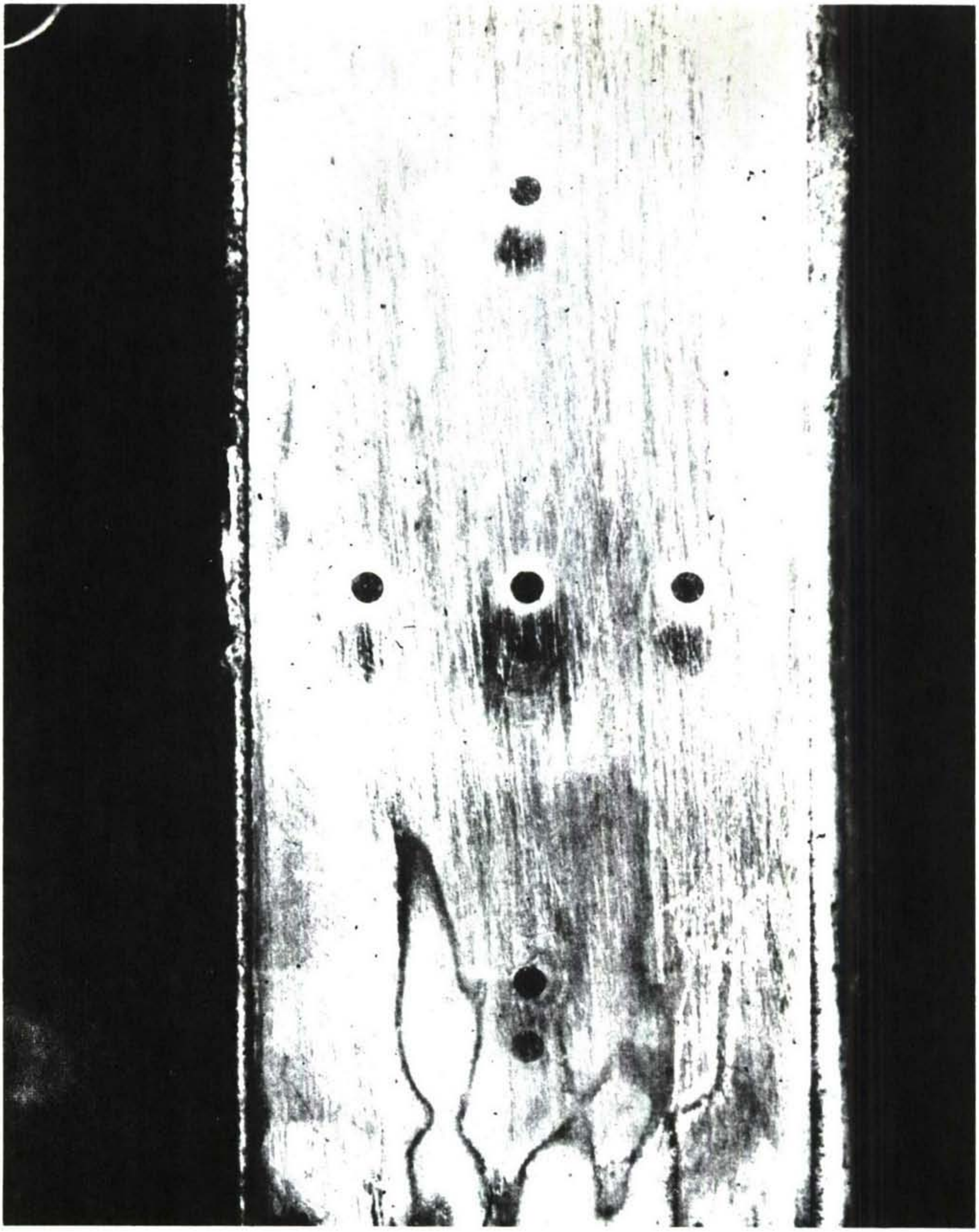


FIGURE 39. VIEW OF DOT DISPLACEMENT BY PHOTOGRAPHIC STRAIN MEASUREMENT (848°-1340° F.) ON INCONEL X-750

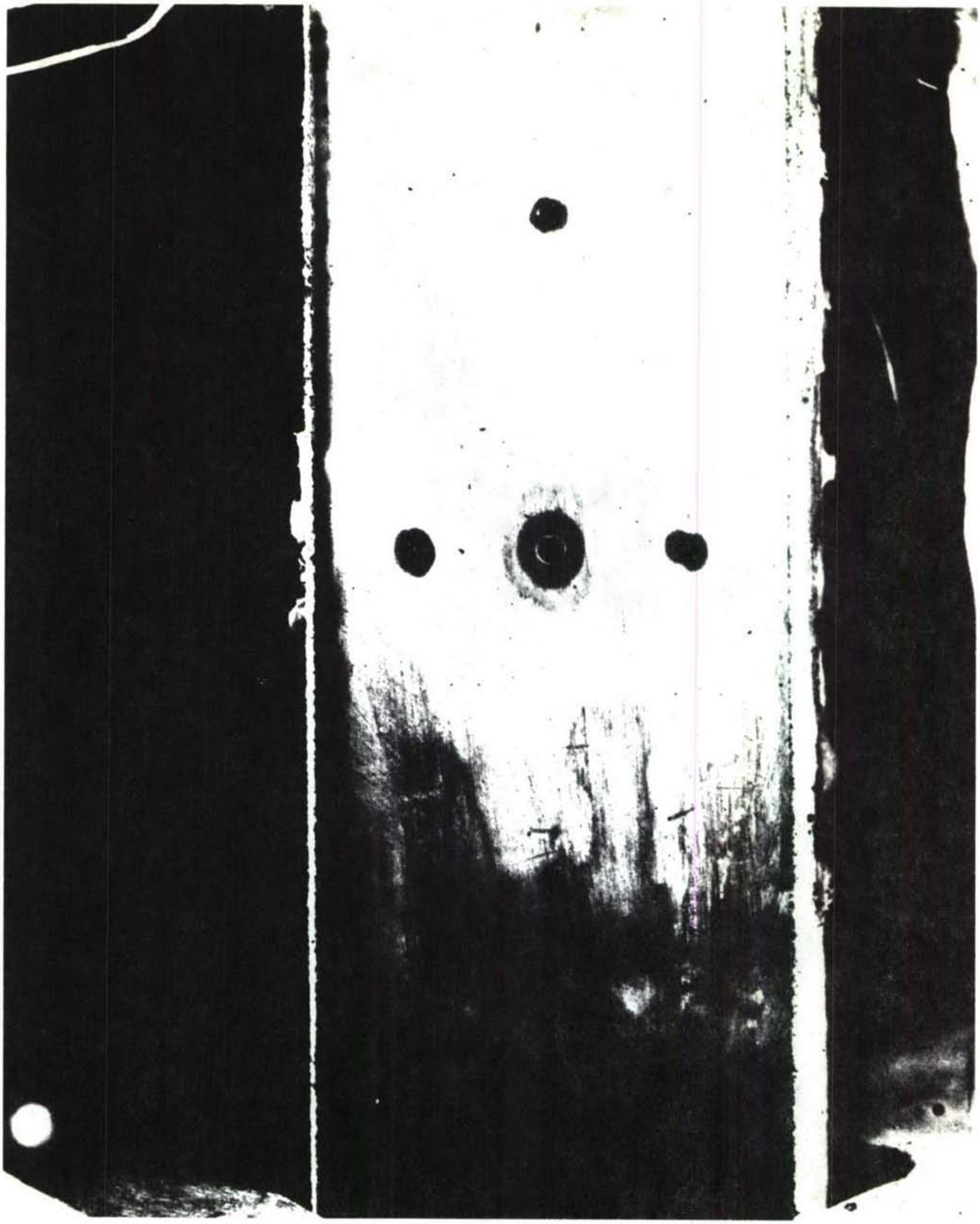


FIGURE 40. VIEW OF THE DOTS PRIOR TO ITS FAILURE ON INCONEL X-750

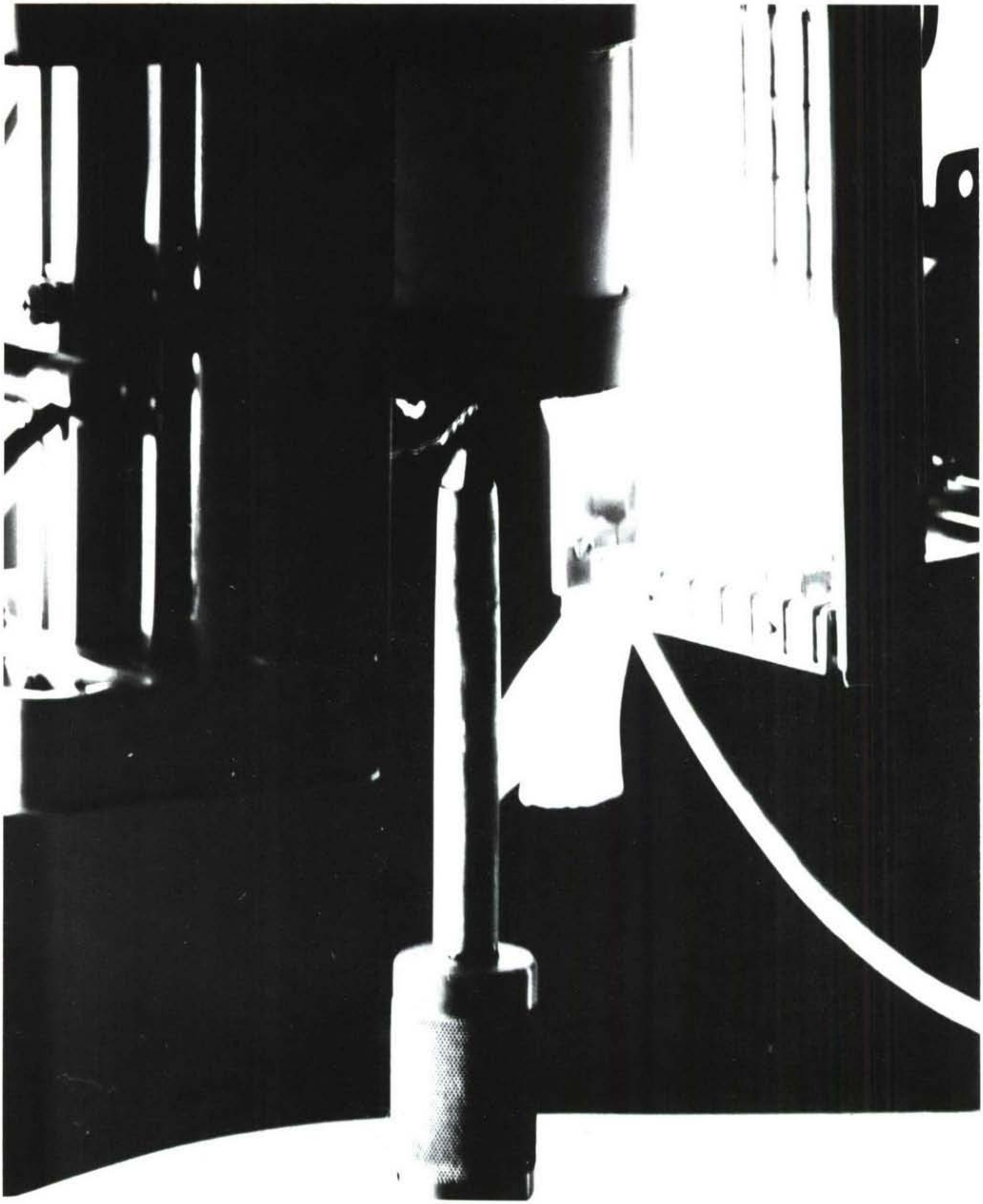
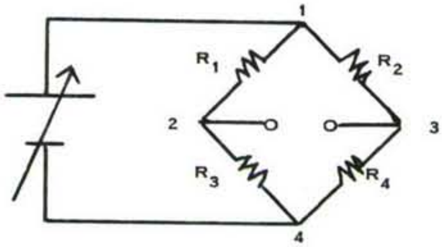


FIGURE 41. VIEW AFTER FAILURE OF INCONEL X-750

TABLE 25

EFFECTS OF TEMPERATURE ON RESISTANCE OF A FULL BRIDGE STRAIN GAGE

Specimen Material: Inconel X-750, Specimen No. 2, Gage No. 1



Temp. ° F.	R_1	R_2	R_3	R_4	R_5 (1-4)	R_6 (2-3)
	OHMS					
75	45	45	46	45	59	59
805	53	53	54	54	69	69
983	56	56	56	56	72	72
1260	58	58	58	58	75	75
1390	59	59	59	59	77	77
1480	60	60	60	60	78	78
1550	60	60	60	60	78	78
1620	62	62	62	62	78	79
1700	58	59	59	60	77	77
75	37	37	38	38	49	49 (Return to 75° F.)

Test performance of gage No. 2 installed on an Inconel X-750 specimen identified as test specimen No. 1, is shown below:

The strain sensitivity of the gage was determined previously at room temperature as indicated on page 59. The test specimen's installation was similar to specimen No. 2 explained previously on page 97. The output of the gage was monitored on a strain indicator at a gage factor setting of 4.00 during the mechanical loading of the specimen. The specimen was subjected to a tensile load from 0 to 6000 lbs., at each of the following temperatures: 75° F., 866° F., and 1100° F. The photographic strain measurements were recorded at 75° F., for a mechanical load of 150 and 11,500 lbs., and at 1086° F., at 150 and 7150 lbs. The coefficient of thermal expansion was then determined by recording the dot displacement at subsequent temperatures of 866° and 1415° F.

Stress-strain values determined for a cross-sectional area of 0.2774 sq. in., (Inconel X-750 test specimen No. 1) are indicated below.

The handbook modulus change vs. temperature is as follows:

31.00×10^6 psi	- 75° F.
26.70	- 866°
23.80	- 1100°
20.00	- 1400°

Load Lbs. (F)	Stress Psi	Strain 75° F.	Strain 866° F.	Strain 1100° F.
150	540	17	20	22
1000	3,609	116	136	-
2000	7,209	233	272	303
3000	10,817	349	408	454
4000	14,419	465	544	606
6000	21,629	698	816	909
7150	25,775	831	973	1083
8000	28,839	930	1088	-
9000	32,444	1047	1224	-
11150	40,194	1296	1517	-
16000	57,678	1860	-	-

Temperature sensitivity measurement on two Full Bridge strain gages is shown in Table 26.

The results of the elevated temperature test were as follows:

Temperature distribution during the test (see Figure 38) was as indicated below:

Elapsed Time Minutes	T/c 1 (Upper Enc)	T/c 2 (Upper Gage Length)	T/c 3 (Lower Gage Length)	T/c 4 (Lower End)	T/c 5 Gage 1	T/c 6 Gage 2
	° F.	° F.	° F.	° F.	° F.	° F.
65	1020	864	910	1157	868	872
78	1062	882	907	1111	875	877
82	1079	874	893	1094	864	866
135	1088	866	866	1077	860	860
180	1444	1090	1090	1459	1100	1100
190	-	1085	1085	-	1050	1050
-	1866	1415	1415	-	1346	1346

TABLE 26

EFFECTS OF TEMPERATURE SENSITIVITY MEASUREMENT ON TWO FULL BRIDGE STRAIN GAGES

Specimen Material: Inconel X-750 Test Specimen No. 1

Strain measurements made on a strain indicator at gage factor of 4.00.

Duration of test: 2 hours.

1st Cycle

Temp. ° F.	Strain Measurements Gage 1	Gage 2
75	-	-
287	2765	2670
780	8520	9070
1124	10925	11020
1230	11645	11365
1400	11665	12430
1411	11930	12265
1663	12680	12935
75	-1275	-3005

Strain measurements recorded during the thermal and mechanical loading:

Temp. 75° F.				866° F.				1100° F.			
Load	Strain ~ μ"/"			Load	Strain ~ μ"/"			Load	Strain ~ μ"/"		
Lbs.	Exp.	Calc.	K_s	Lbs.	Exp.	Calc.	K_s	Lbs.	Exp.	Calc.	K_s
Pre-load @150 lbs.	-	17	-	Pre-load @150 lbs.	-	20	-	Pre-load @150 lbs.	-	23	-
1000	180	116	-	3000	565	408	-	3000	585	454	-
2000	360	233	-	6000	1065	816	5.22	6000	1095	909	4.81
3000	560	349									
4000	745	465									
6000	1130	698	6.45								

Temperature sensitivity of the gage recorded during the test:

Temp. ° F.	Strain μ"/"	Δ-Strain ~ μ"/"	Remarks
75	Zero @ 30,000	--	Zero load
866	37950	7950	150 lb. preload
1100	39855	9855	150 lb. preload

Photographic Displacement Due to Mechanical Loading:

Temp. ° F.	Load- Lbs. Zero	Max.	Displacement ~ Inches Initial	Final	Diff.	Strain μ"/" Exp.	Calc.	Stress Psi	Modulus x 10^6 Psi
75	0	16000	0.5330	0.5340	0.0010	1872	1860	57678	31
1086	150	7150	0.5926	0.5933	0.0007	1181	1083	25775	23.8

Photographic Displacement Due to Thermal Expansion:

Temp. ° F.	ΔT	Displacement Initial L_0	Final L_1	Inches Diff. ΔL	Coefficient of Thermal Expansion Exp.	Handbook
866-1415	549	0.5917	0.5949	0.0032	9.805×10^{-6}	9.2×10^{-6} (75-1600° F.)

The following method was used in determining the thermal coefficient of expansion:

$a_L = \frac{1}{L}\frac{dL}{dt}$ = the relative rate of change of length with respect to temperature

if a_L = constant

then $a_L \int_{T_1}^{T_2} dt = \int_{L_1}^{L_2} \frac{dL}{L} = \left[\ln L\right]_{L_1}^{L_2} = \ln L_2 - \ln L_1 = \ln \frac{L_2}{L_1}$

$$a_L (T_2 - T_1) = \ln \frac{L_2}{L_1}$$

$$a_L = \frac{\ln \frac{L_2}{L_1}}{T_2 - T_1} = \frac{\ln \frac{L_2}{L_1}}{\Delta T}$$

L_2 = 0.5949 = final length

L_1 = 0.5917 = initial length

$$\frac{L_2}{L_1} = \frac{0.5949}{0.5917} = 1.00541$$

$\ln 1.00541 = \ln 100.541 - \ln 100$

$\ln 101 = 4.61512$

$\ln 100 = \underline{4.60517}$

$\quad\quad\quad\quad 0.00995$

$0.541 \times 0.00995 = 0.005383$

$\ln 100.541 = 4.60517 + 0.005383$

$= 4.610553$

$\ln 1.00541 = 4.610553 - 4.605170$

$= 0.005383$

$$a_L = \frac{\ln 1.00541}{\Delta t} = \frac{0.005383}{549} = 9.805 \times 10^{-6}$$

Since these are point functions, they do not depend upon the arbitrary choice of an initial temperature. These coefficients can be integrated between any two temperatures.

At completion of the test, a strain sensitivity measurement was performed on gage No. 2 at room temperature. Both the optical gage and the strain gage outputs were recorded as shown in Table 27.

The results of the tests demonstrate that is stress is maintained constant during a variation in temperature, causing a modulus (E_M) change, then the bridge sensitivity factor (K_s) will either increase or decrease as a function of E_M in straight line of the stress-strain curve. This can be proved by the following equation from page 108,

$$K_s = \frac{4 \Delta E_g}{E_i \, e}$$

But $e = \frac{S}{E_M}$ where S is the stress and E_M is the modulus of elasticity

$$\text{Then } K_s = \frac{4 E_M \Delta E_g}{E_i \, S}$$

hence K_s is a function of E_M.

TABLE 27

STRAIN SENSITIVITY MEASUREMENTS ON A FULL BRIDGE STRAIN GAGE AT ROOM TEMPERATURE AFTER COMPLETION OF TESTS AT ELEVATED TEMPERATURES

Specimen material: Inconel X-750 test specimen 1, gage 2.

True strain observed on a 1" optical gage.

Strain measurements observed on a strain indicator at gage factor of 4.00.

Load Lbs.	Strain	True Strain
1000	160	128
2000	320	256
3000	485	384
4000	665	512
5000	840	632
6000	1020	760
7000	1195	880
8000	1360	1016
7000	1220	888
6000	1045	768
5000	875	632
4000	700	504
3000	530	376
2000	360	232
1000	195	104
0	30	-32

R-cal. equivalent at 30,000 ohms

Before test	485/540
After test	425/455

Bridge resistance

Before test	64.63 ohms
After test	50.00 ohms

SUMMARY AND CONCLUSIONS

The Full Bridge resistance type strain gage consists of four elements that have identical thermal characteristics. The two opposite strain sensitive arms sense changes in strain and temperature while the remaining two arms sense only the changes in temperature.

An Air Force program was initiated in May 1962 for the development of a Full Bridge strain gage usable to 2000° F. The behavior properties of a Full Bridge strain gage were initially investigated to 1200° F. by integration of two Half Bridges into a Full Bridge strain gage. The electrical connections between them were such that the behavior of each Half Bridge strain gage and also of the externally connected Full Bridge strain gage could be determined both at room and elevated temperatures.

Results of this investigation indicate a summation of both the apparent and mechanical strain in a Full Bridge strain gage construction providing that the active arms of each Half Bridge are electrically connected in the opposite arms of a Wheatstone bridge configuration.

Method of attaching a strain gage to test specimens usable to 2000° F. was developed in the use of a flame spraying technique. The flame spraying of nickel chrome and alumina to form substrates on the specimen showed excellent thermal shock and oxidation resistance properties as part of the gage installation techniques for high temperature applications.

The photographic strain measurement system was only partially successful because of the unforeseen problems created at the elevated temperatures. One major drawback in the design of the photographic system was placement of the quartz window. Since only a portion of the window was enclosed in the furnace with the remainder extending outward, the difference in expansion properties between the furnace and the quartz window caused the window at times to deflect, producing an erroneous recording of the displaced markings. The camera, since it was subject to vibration, also produced a large error in the recording of the dots.

The inadequate design of the furnace for use at 2000° F. was clearly indicated. The increase in heat losses at temperatures above 1500° F., and the existence of the temperature gradient across the cross-sectional gage length area of the specimen, limited the use of this furnace to elevated temperature tests of 1500° F.

Consequently, the experimental investigations indicated in this report have shown:

1. Bridge sensitivity factor equal to 6.5 $\pm$ 0.5.

2. Resistance of the bridge equal to 60 $\pm$ 0.5 ohms.

3. Leakage resistance to ground at 75° F. approximately 1000 megohms.

4. Leakage resistance to ground was approximately 10 megohms at 2000° F. at heating rates of 25° F./sec., and 2 megohms at a heating rate of 20° F./min.

5. Negligible drift at 1400° F.:
   1600° F. - 10 micro-inch per inch per minute during the first cycle decreasing to 0.6 micro-inch per minute during its fourth cycle;
   1800° F. - 15 micro-inch per minute in the first cycle decreasing to 0.1 micro-inch per minute during the fourth cycle;
   2000° F. - 20 micro-inch per inch per minute.

6. Maximum current carrying capacity was not less than 300 mv., and 150 mv. at 75° F., and 2000° F. respectively.

7. Temperature sensitivity at 2000° F. was approximately 12,000 micro-inch per inch during its first cycle when measured on a strain indicator at a gage factor setting of 4.00. The temperature sensitivity was directly proportional to the bridge voltage.

8. Gage physically capable of withstanding continuous cycles to 2000° F., at heating rates of 100° F./sec.

9. Equal change in resistance in all the arms of the bridge when measured to 2000° F.

10. No loss in strain sensitivity of the gage to 1100° F.

The results of the tests at elevated temperatures have further indicated that the Iridium alloy in the HT-1200 material diffuses when exposed to an oxidizing atmosphere at approximately 1500° to 1600° F. during its first thermal cycle. However, during the succeeding thermal cycles the material stabilizes and is useable

for static strain measurements above 1600° F. This has been shown by the decrease in resistance at approximately 1600° F., and a high change in the temperature coefficient of resistance.

Electrical resistivity and temperature coefficient of resistance of some platinum-iridium alloys is indicated below:

Percent Iridium	Resistivity 20° C ohms/cmf	Temperature Coefficient of Resistance 10 - 160° C
5	115	0.0020
10	150	0.0013
15	170	0.0010
20	190	0.0008

The above table shows a decrease in resistance and an increase in temperature coefficient of resistance for a decrease in the alloy content.

RECOMMENDATIONS

Results of experimental studies conducted on a Full Bridge strain gage made from a platinum-rhodium alloy instead of the platinum-iridium alloy used for the present gages showed a linear temperature gage response over the temperature range of 75° to 2000° F. There was no zero shift on its return to room temperature.

A resistance change vs. temperature variation is shown below:

$R_{1,3}$ ohms	$R_{2,4}$ ohms	Temp. ° F.
33.18	33.85	75
60.00	61.21	1200
33.07	33.72	75
71.74	70.15	1850
32.97	33.55	75

Further studies performed on a Full Bridge coupon type gage as indicated below showed gage stability after its exposure to 1200° F. for a period of 24 hours.

Effects of temperature sensitivity on the Full Bridge strain gage are tabulated below. Strain measurements were recorded at gage factor setting of 6.5.

Time Minutes	Temperature ° F.	Gage No. 1: Strain Zero set at	Gage No. 1: - Strain
0	95	5230 μ"/"	
10	200	4830	400 μ"/"
19	400	4330	900
38	600	3720	1510
79	800	3100	2130
99	800	3110	2120
180	800	3100	2130
240	800	3090	2140
300	400	4350	880
420	260	4730	500
	95	5280	+50

Additional work towards the evaluation of a Full Bridge strain gage for use to 2000° F. and beyond appears to be warranted. This would include chemical assaying and spectograph analysis to establish possible changes in the nominal mixture ratio of elements in each alloy as well as to determine the presence of contaminating influences.

Further study of heat treating and aging treatment of wire should be made to develop a stabilizing procedure for continuous strain gage usage at the higher temperature limit.

A need also arises for use of resistance thermometers in place of thermocouples to record temperature changes at heating rates in excess of 50° F./second.

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) High Temperature Instruments Corporation Philadelphia, Pennsylvania	2a. REPORT SECURITY CLASSIFICATION Unclassified
	2b. GROUP

3. REPORT TITLE
A Full Bridge Type Strain Gage for Use at Elevated Temperatures

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final Report

5. AUTHOR(S) (Last name, first name, initial)
Sokolcwski, Benedict A.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
April 1965	127	None

8a. CONTRACT OR GRANT NO. AF 33(657)-11713	9a. ORIGINATOR'S REPORT NUMBER(S) FDL-TDR-64-54
b. PROJECT NO. 1347	
c. Task Nr. 134702	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

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(1), (2)/DDC release to CFSTI is not authorized.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
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13. ABSTRACT

The two-fold purpose of Contract Nr. AF 33(657)-9295 from June 1962 to March 1963 was as follows: (1.) Development of a Full Bridge strain gage; (2.) Gage installation methods usable to 2000°F. The work conducted under Contract Nr. AF33(657)-11713 from May 1963 to November 1963 consisted of a study of the characteristics of a Full Bridge strain gage over a temperature range of 600°F to 2000°F. The following tests were performed: (1.) Measurement of bridge sensitivity factor (2.) Gage drift at constant temperature; (3.) Response of gage to rapid radiant heating; (4.) Leakage to ground resistance measurement; and (5.) Self heating effects. It is shown that: (1.) Gage installation by means of flame sprayed material was adequate for use to 2000°F; (2.) Average bridge sensitivity factor was 7.0±0.5 as measured at room temperature with a slight decrease at 1100°F; (3.) Self heating effects of the gage were minimized; (4.) Gage demonstrated a negligible drift rate to 1400°F; and (5.) Leakage resistance when measured at 2000°F, at a heating rate of 50°F/second was 10 megohms. However, the gage material selected on the basis of previous tests was not fully acceptable for gage use to 2000°F, because a metallurgical transition occurs above 1500°F.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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3. Laboratories & Test Facilities; test equipment, test methods						
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